Unveiling the chemical+dynamical correlations in the Milky Way

Thursday, June 6, 2019 – 11.00 - 12.15

Melissa Ness (Flatiron/Columbia, NYC)

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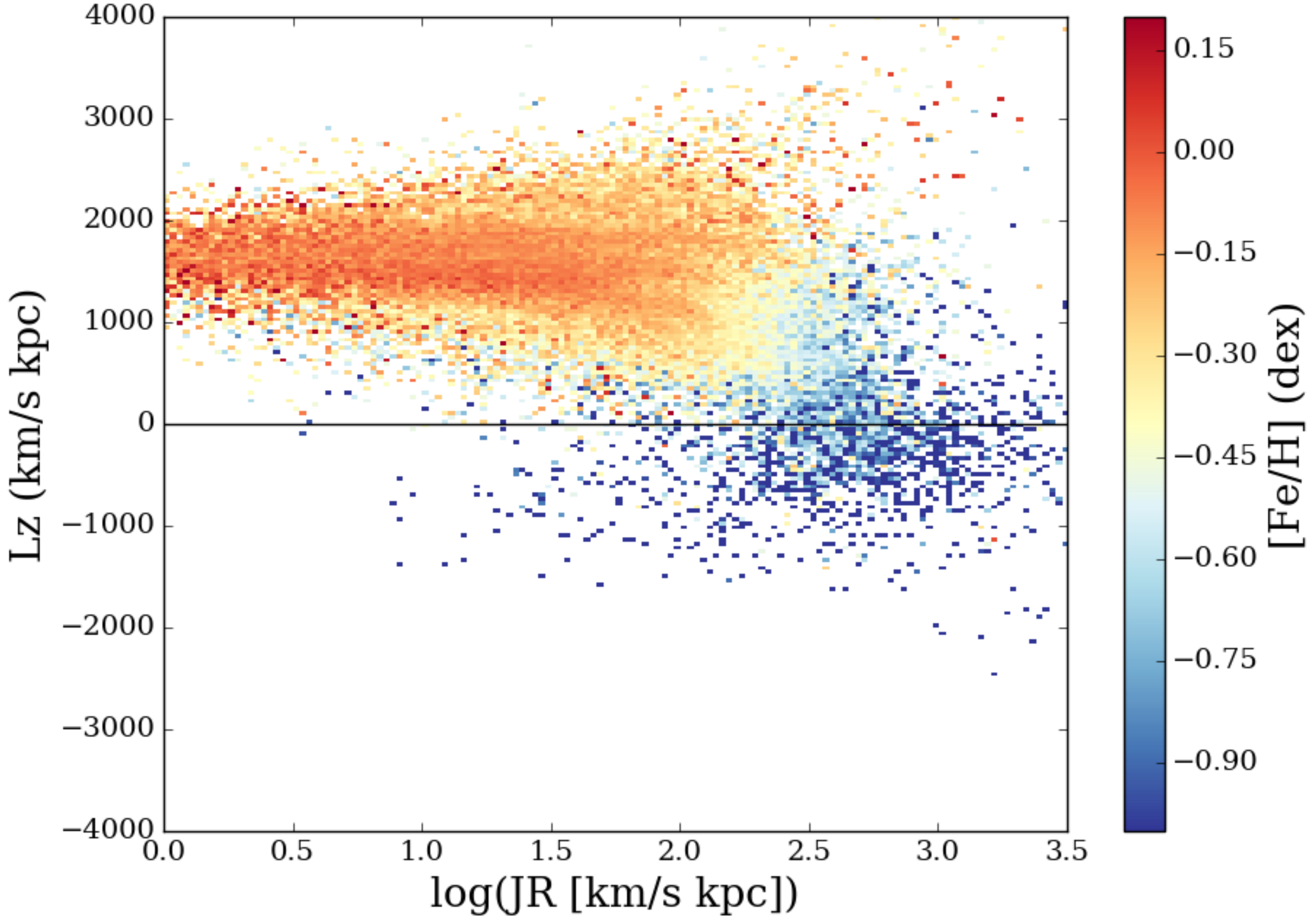
What on earth is this plot and what does it show?



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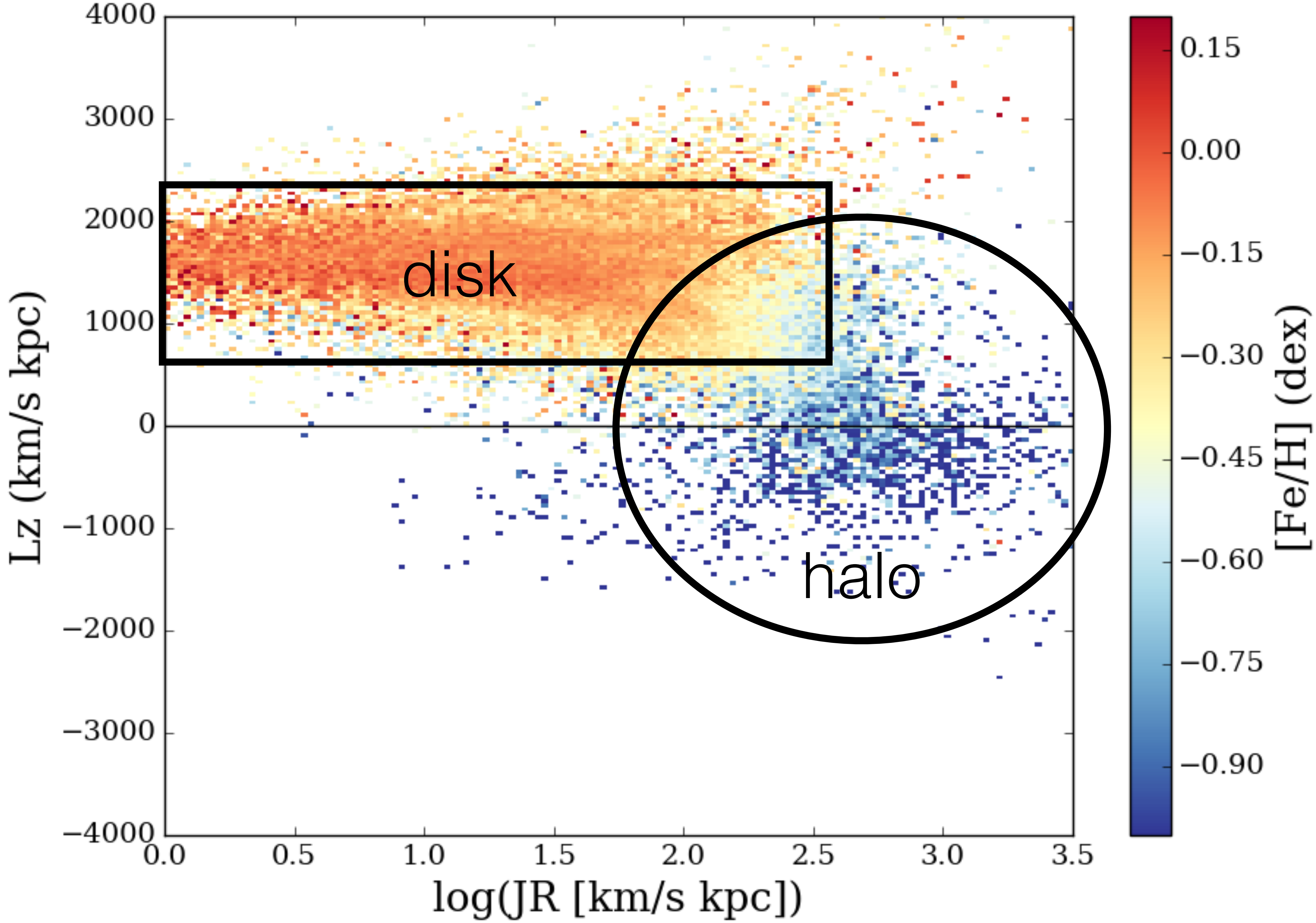

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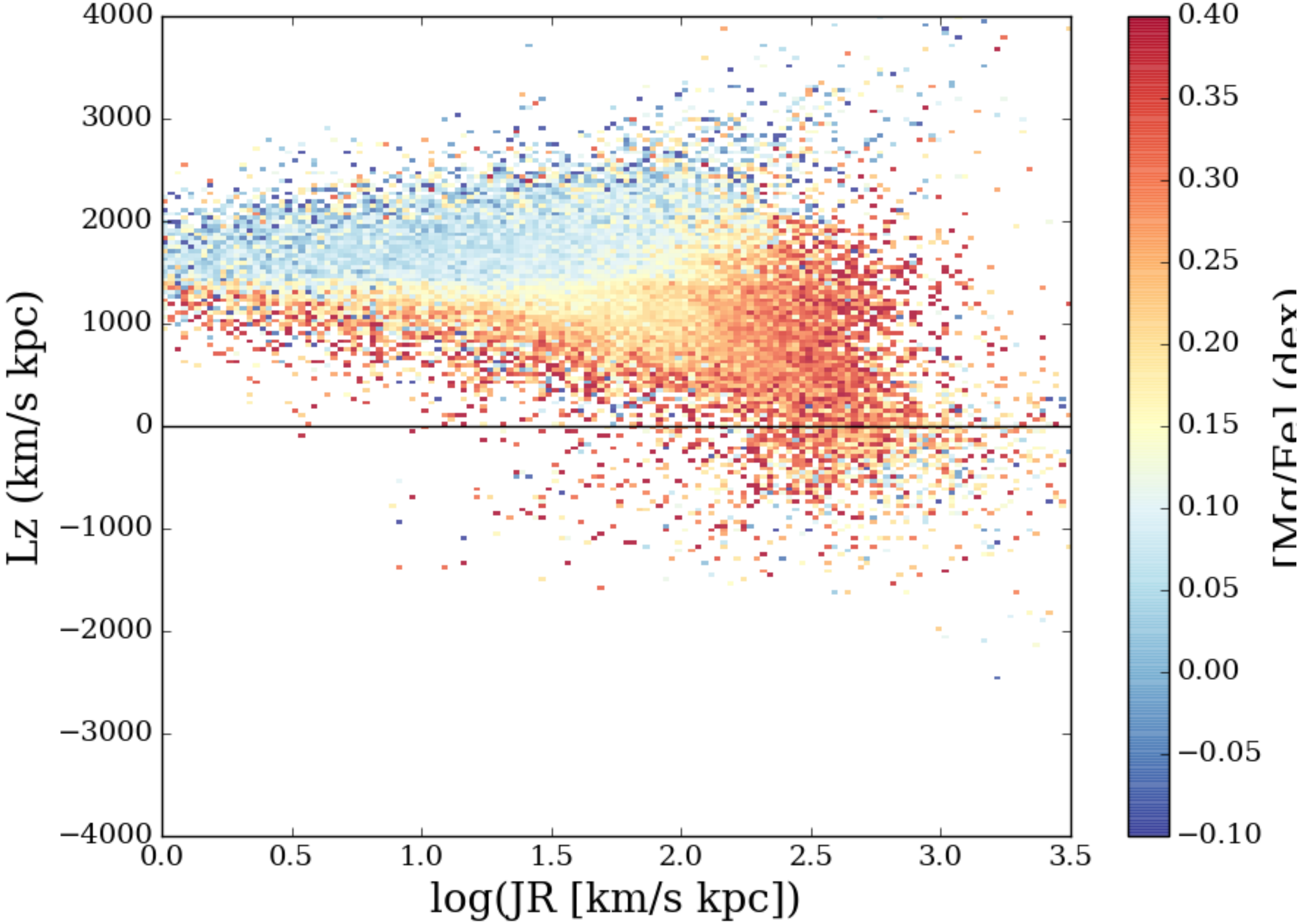

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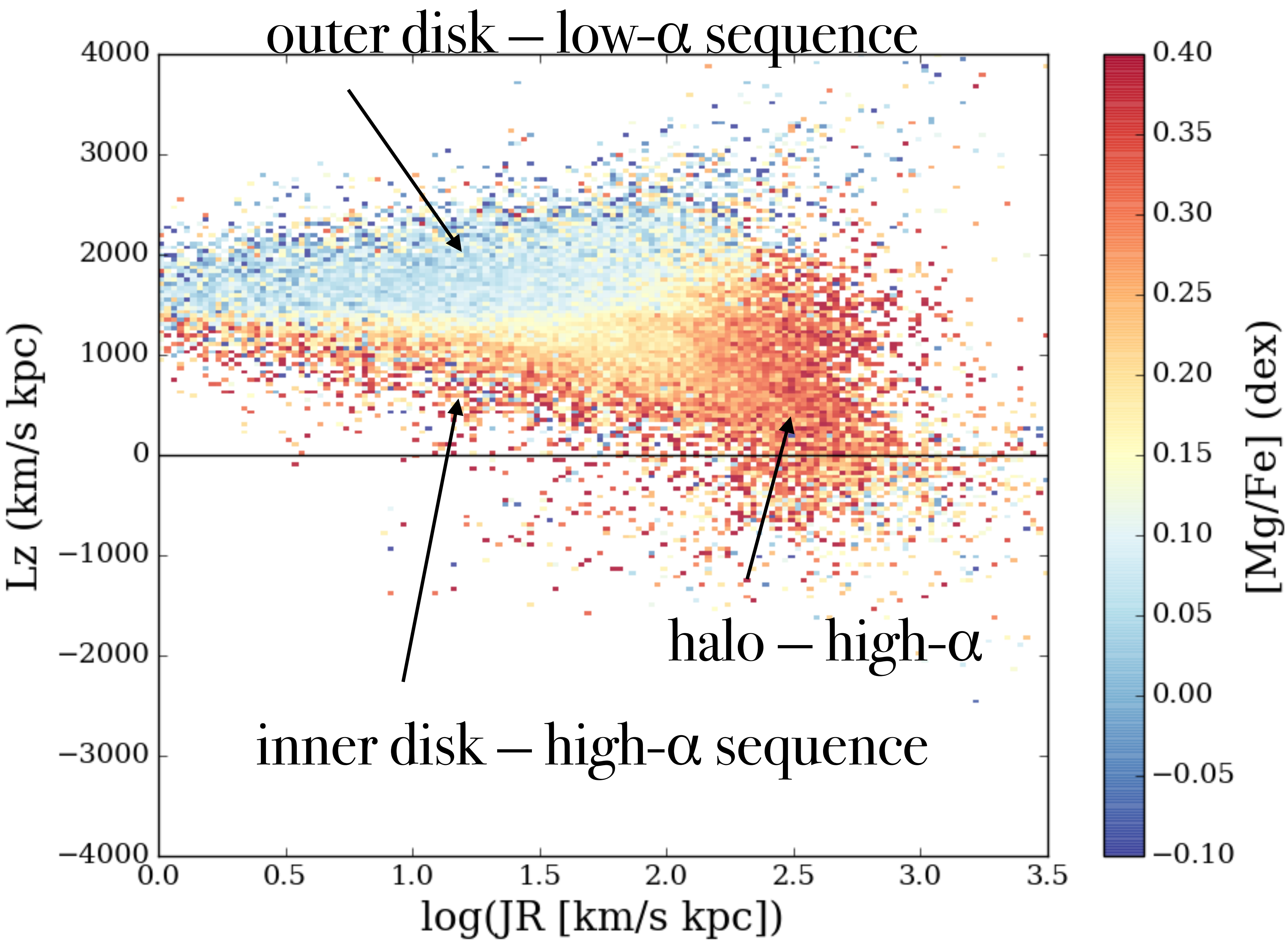
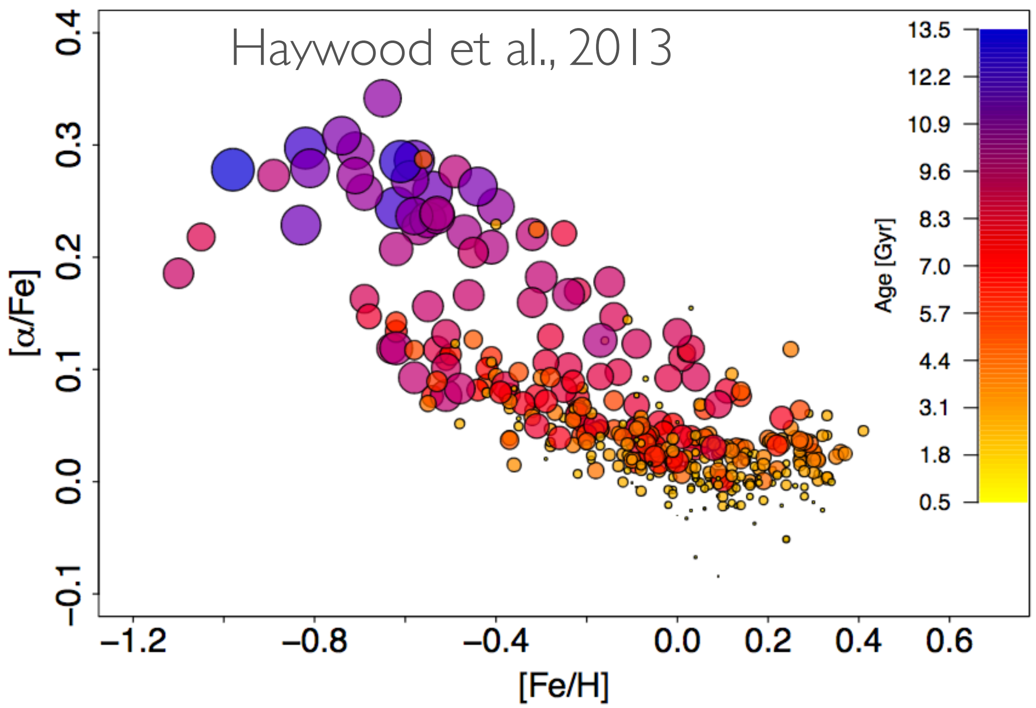
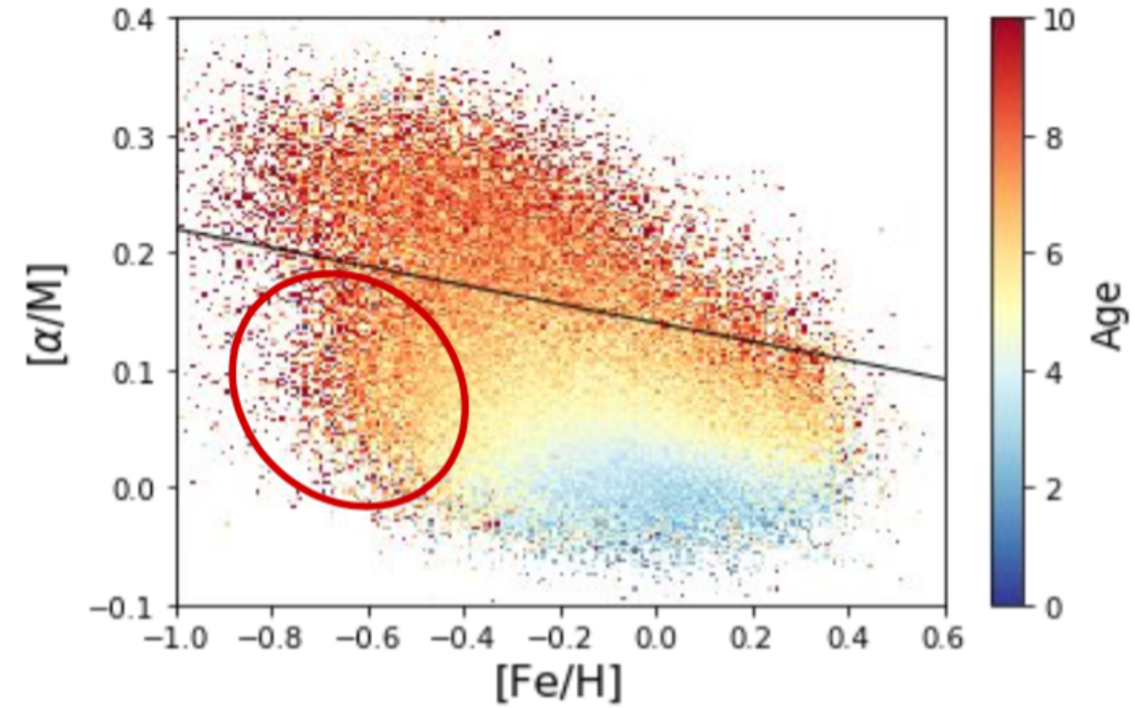
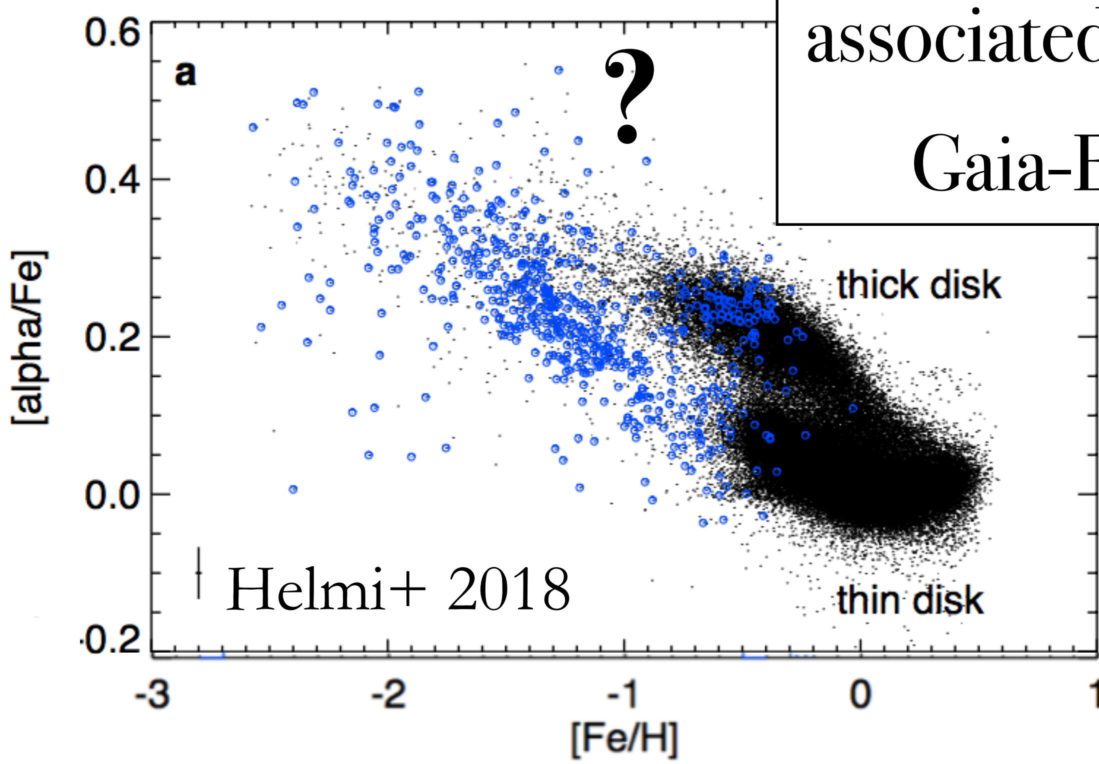


“Outliers” – there are old alpha-poor stars!



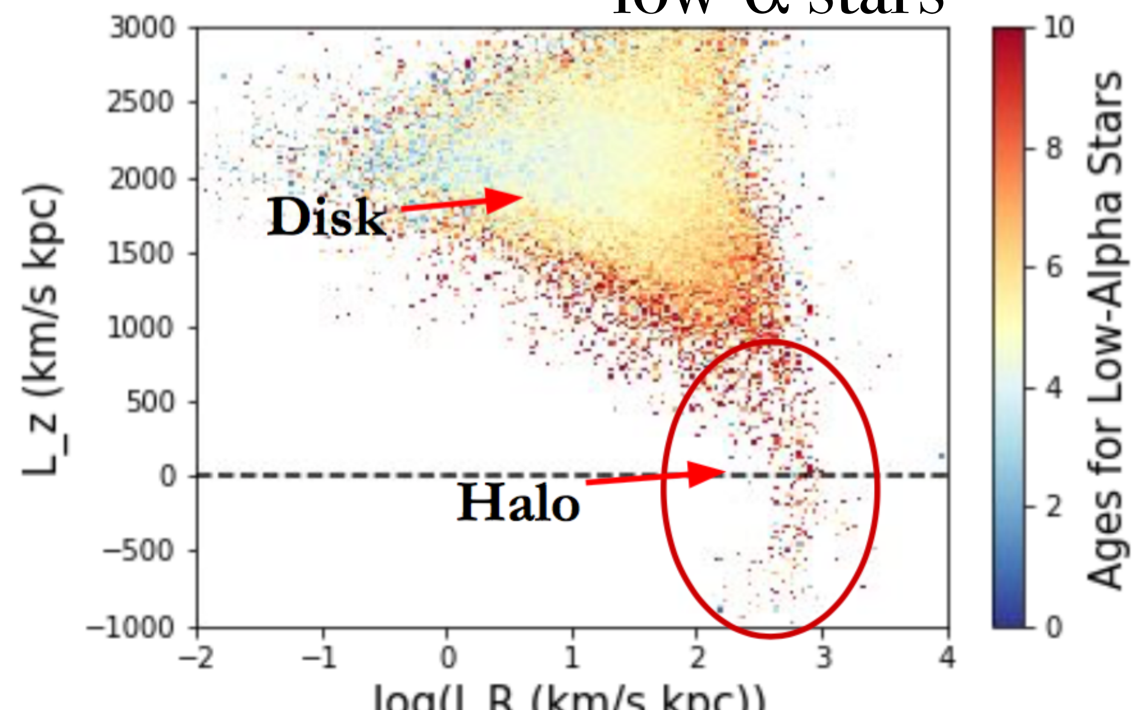




associated with

Gaia-E?

low-α stars

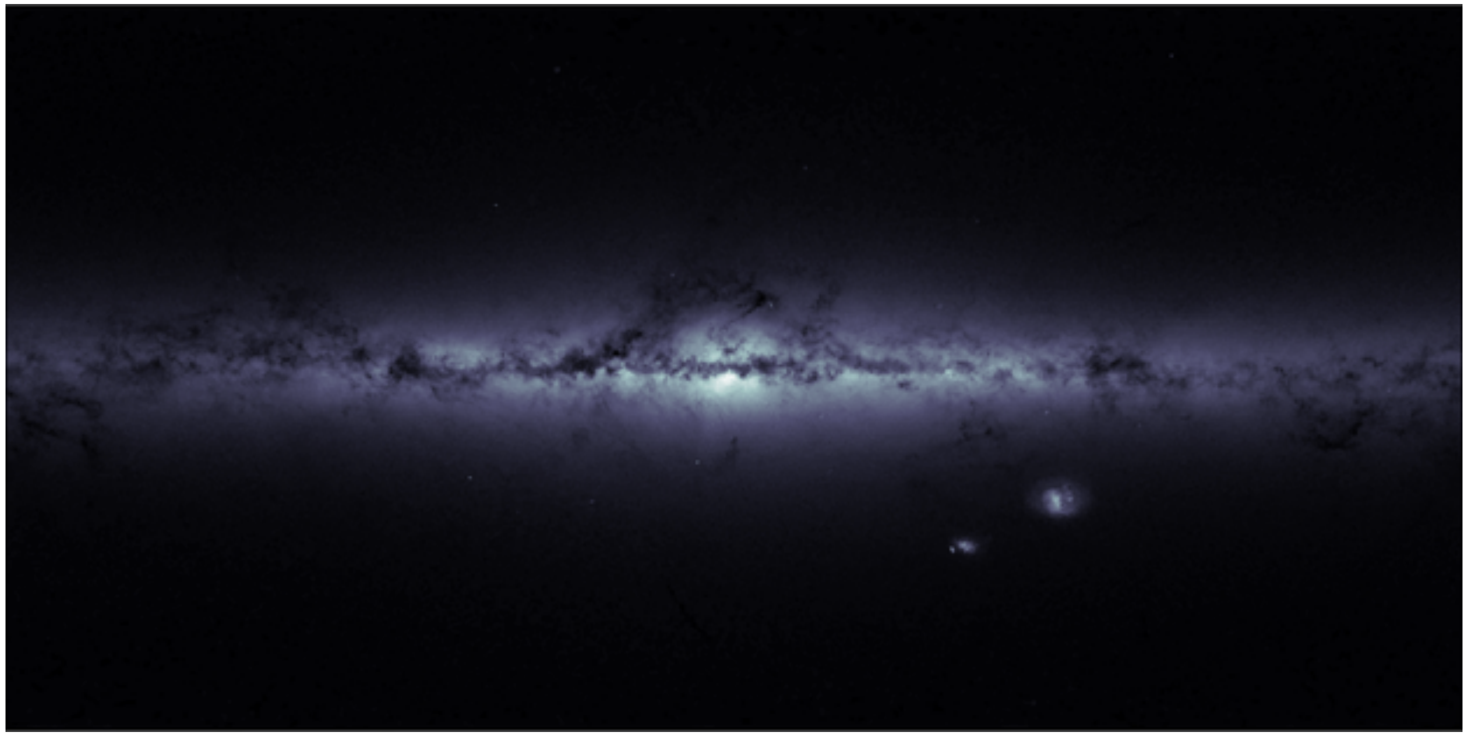


In Data-Driven Pursuit of Galactic Archaeology

- The Milky Way is a typical spiral galaxy
- stellar mass – 75% in the **disk**, 24% is in the **bulge**
- We can resolve individual **stars** & derive a set of measurements from these stars
    - p(**age, mass, chemical composition,** orbits)

stellar spectra

satellite missions measuring movement



All sky-density map of the 1.1 billion sources in Gaia DR1 (ESA/Gaia/DPAC/U.Lisbon)

The key diagnostics: *stellar ages and precision abundances*

How many stars born & when, from what material, on what orbit

How the orbits on which stars were born subsequently change?

→ *(i) chemical composition [X/Fe]* → *(ii) stellar ages*

What do we learn from all of the individual abundances?

(age, [Fe/H], [X/Fe])

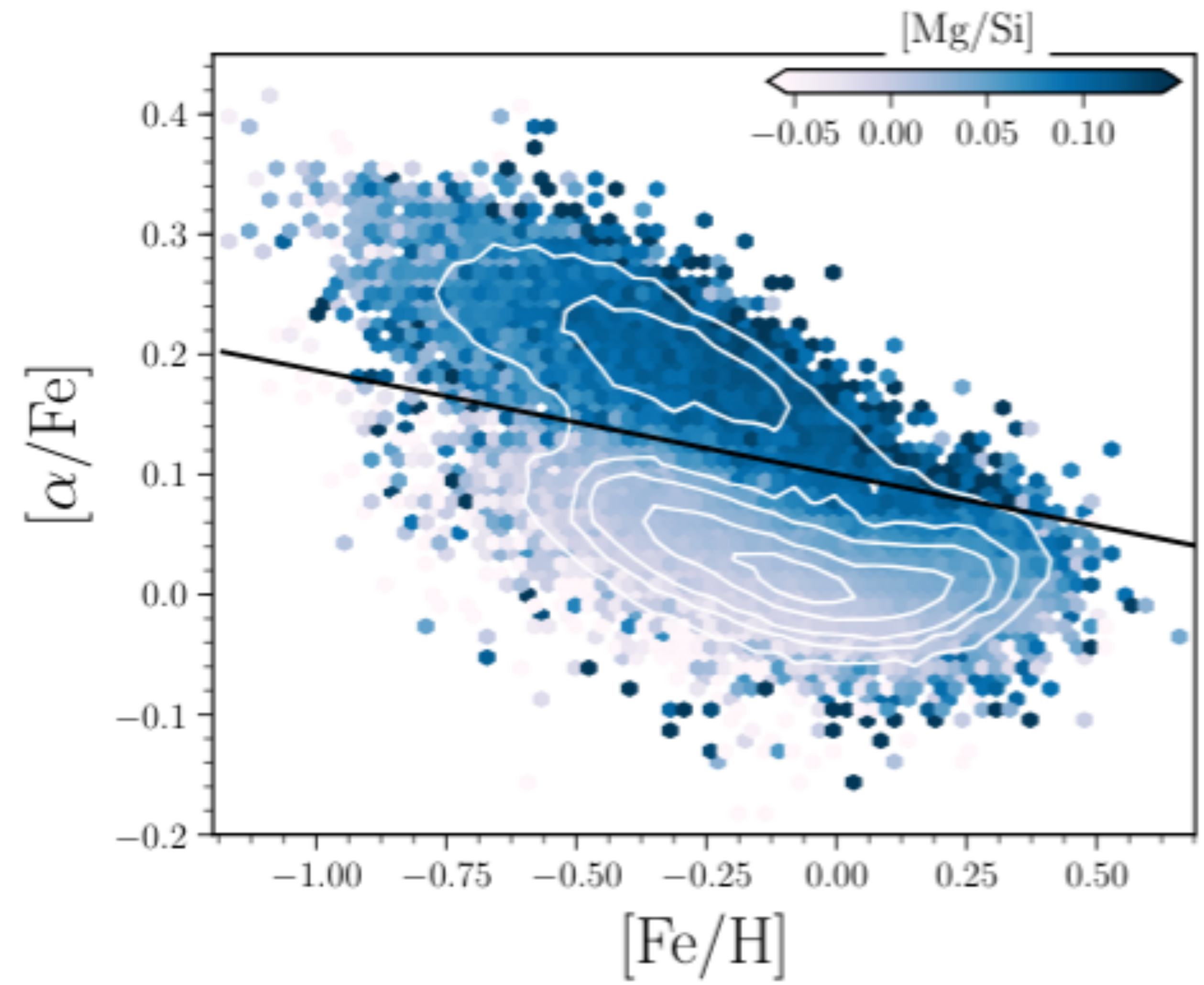
what does the [X/Fe] tell us?

Let's start with two

2 x alpha-elements | [Mg/Fe] and [Si/Fe]

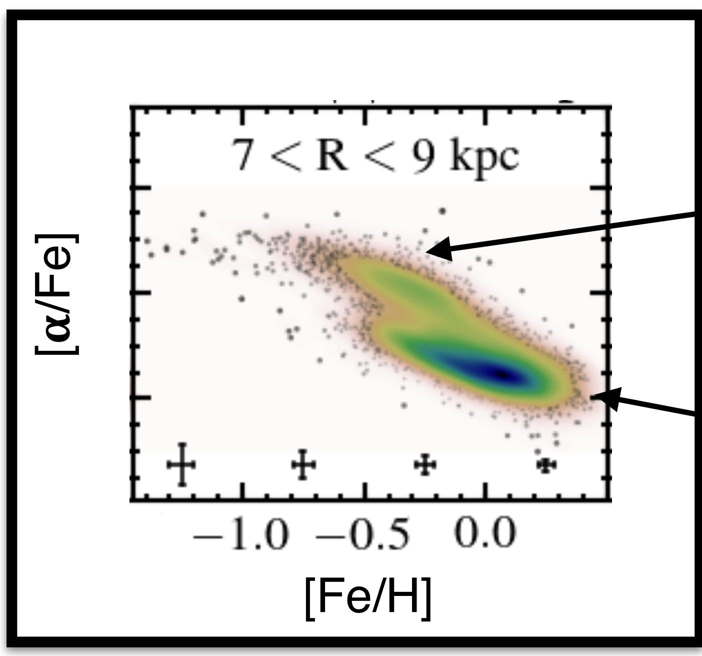
Variations in α-element ratios trace the chemical evolution of the disk

Kirsten Blancato (Columbia



Motivation

Well established that the chemical structure of the Milky Way exhibits a bimodality in α-enhancement versus [Fe/H] - learned a lot



fast enrichment, concentrated to inner Galaxy

slow enrichment, concentrated to outer Galaxy

Inspired by the expected subtle differences in their nucleosynthetic origins, we probe the higher level of granularity encoded in the inter-family [Mg/Si] ratio

Different Nucleosynthetic origins

- "While the α-elements O, Mg, Si, Ca, and Ti are often treated as a homogeneous group, they do not all originate from the same process" Carlin+ 2018

- Mg - hydrostatic nucleosynthesis produced in massive stars (yield mass dependent)
- Si - explosive nucleosynthesis produced in explosion itself (yield mass independent)

- Sagittarius dwarf galaxy: Mg low, Si high 'top light' IMF (McWilliam et al. 2013; Hasselquist et al. 2017; Carlin et al. 2018)

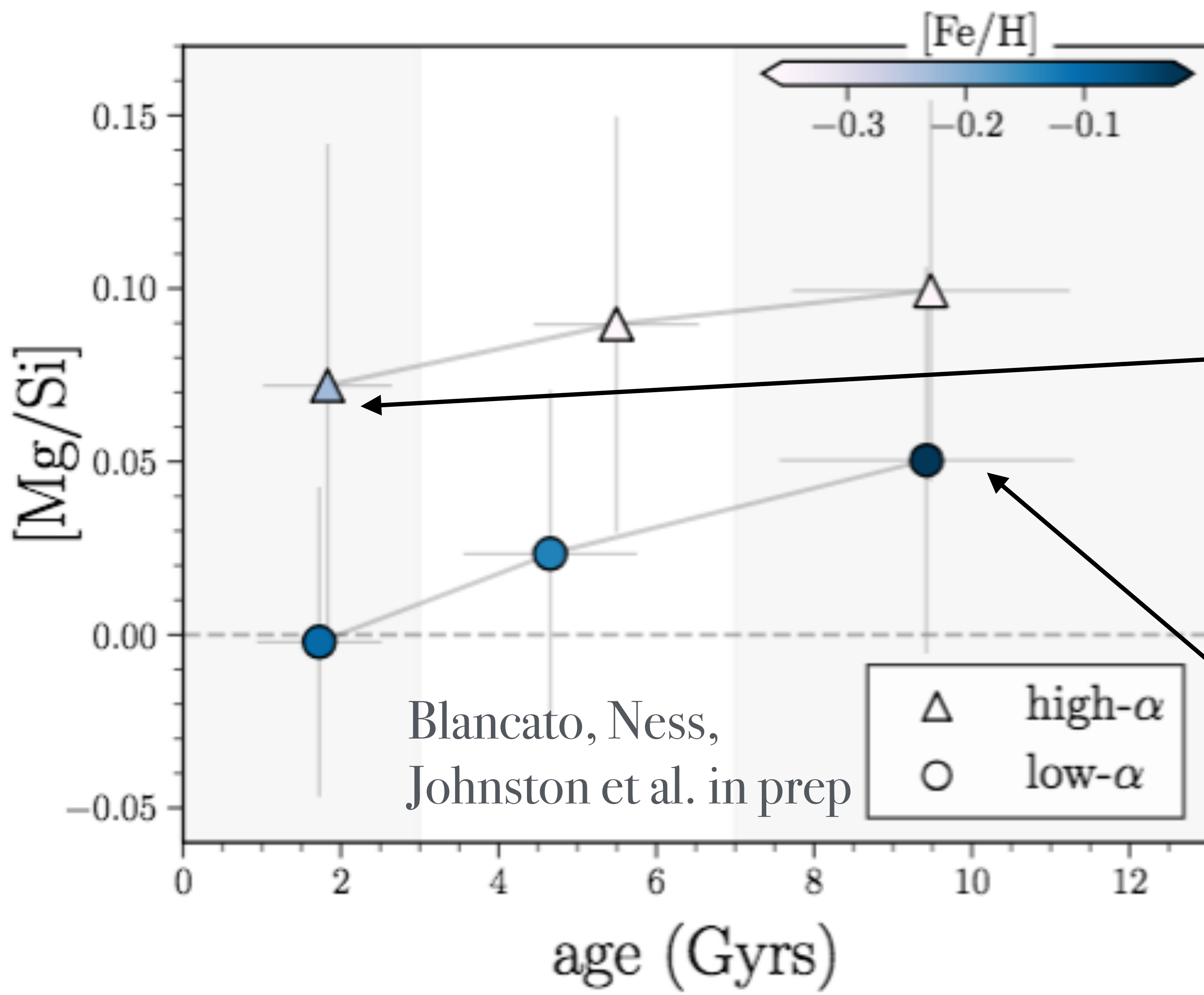
- How does the [Mg/Si] ratio vary across the disk of the Milky Way and might this constrain the IMF across the disk?

Our Data and Results

- 100,000 APOGEE red giants with abundances, Gaia astrometry, and stellar age
- Characterize the relationships between [Mg/Si], α-enhancement, age, [Fe/H], location, and orbits.

- Disk formed inside-out with radially stratified chemical enrichment at a given time

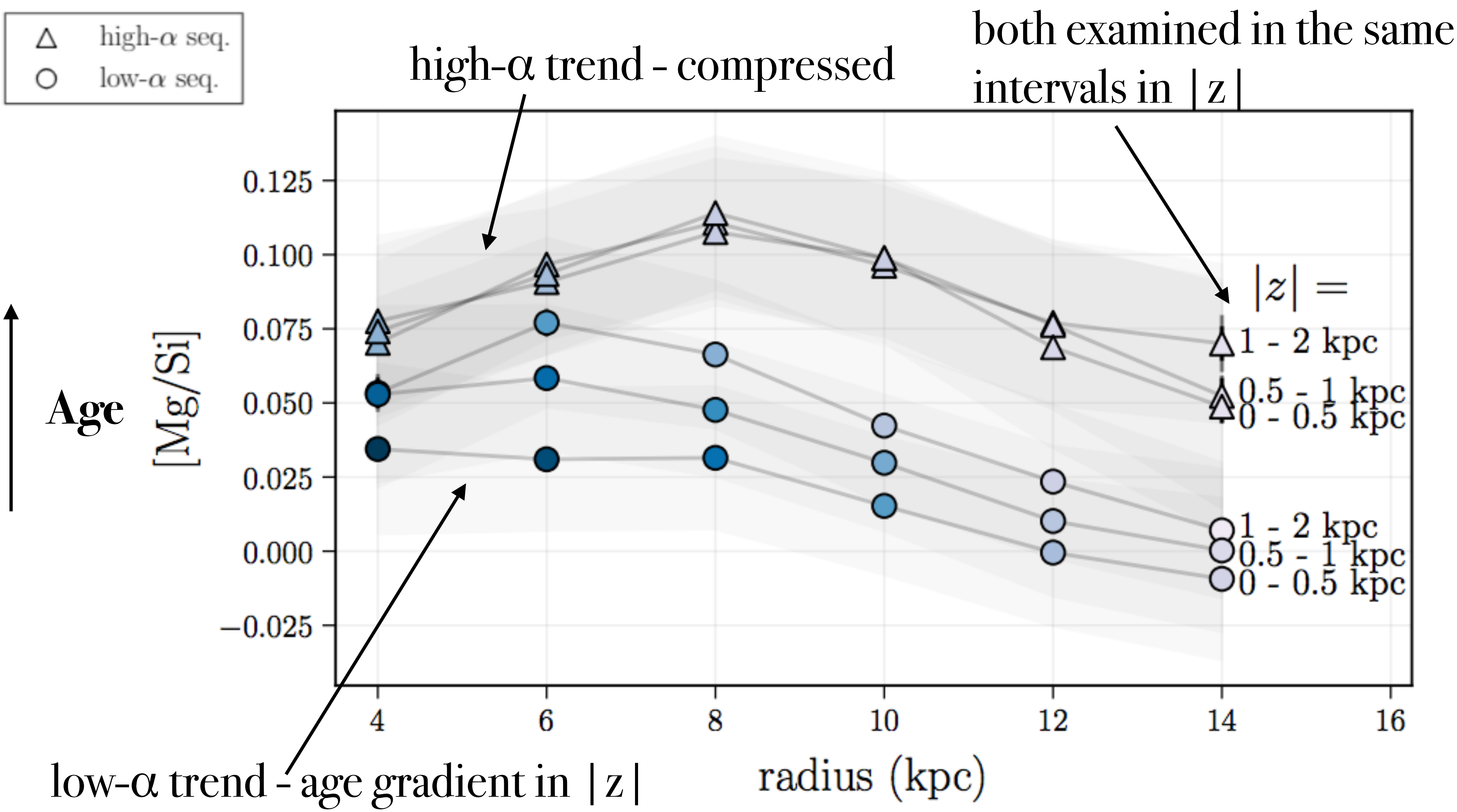
[Mg/Si] traces age



high-α sequence: most metal rich stars youngest

low-α sequence: most metal rich stars oldest

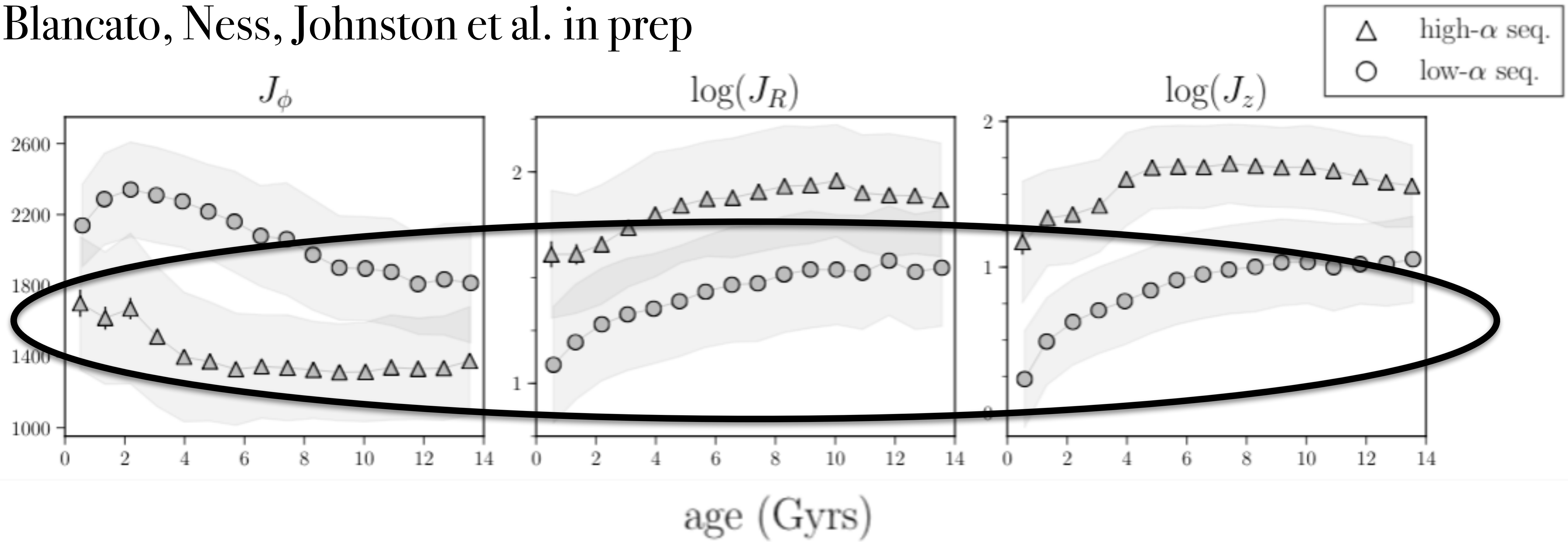
[Mg/Si] varies across the disk for the low and high α-sequences



Blancato, Ness, Johnston et al. in prep

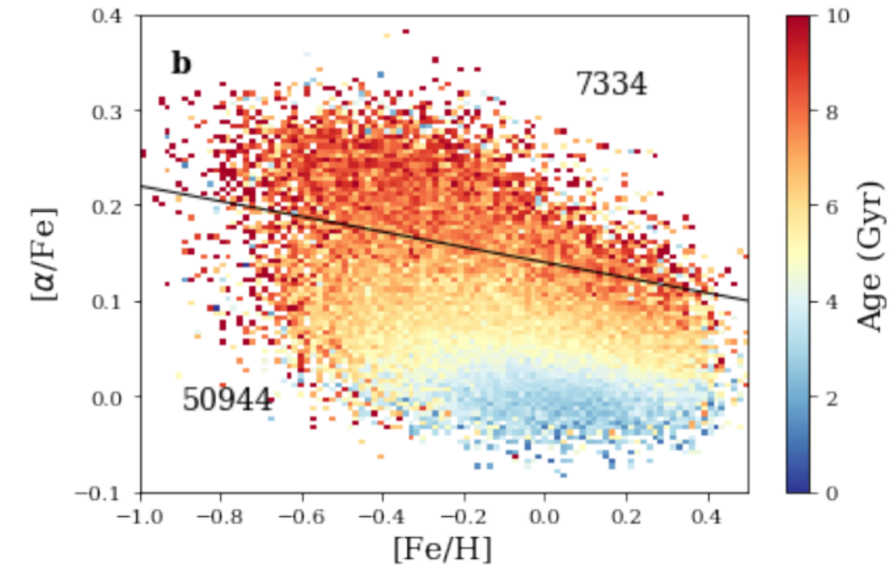
At a given age, low and high α stars separate dynamically

Blancato, Ness, Johnston et al. in prep



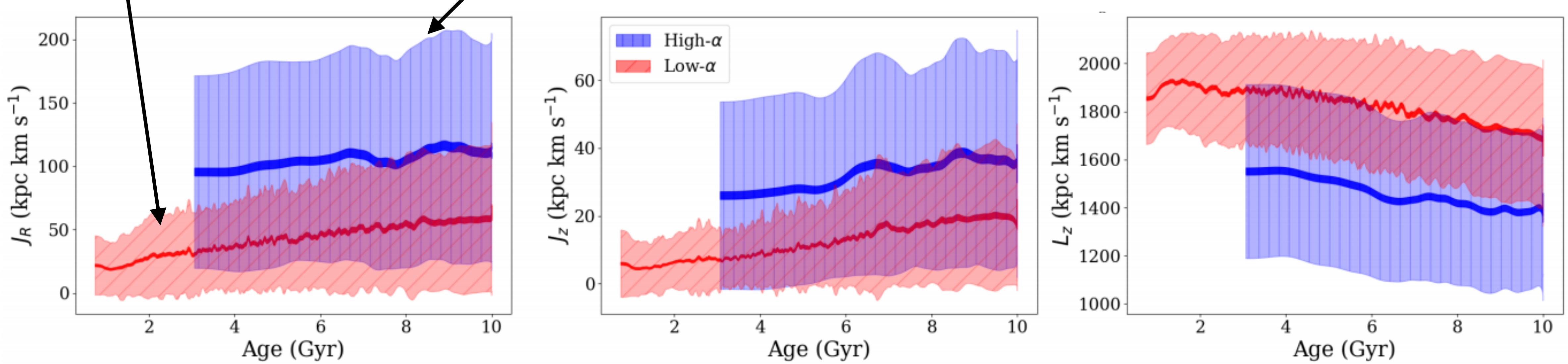
What sets the orbit of a star: age or chemistry?

JR: Radial Action → eccentricity
Jz: Vertical Action → height above plane
Jφ (or Lz): Angular Momentum →orbital radius



low-α LAMOST stars

high-α LAMOST stars



A star's membership in the high- or low-α sequence indicates its dynamical properties at a given time

Implies separate formation and evolutionary histories for the two sequences

Gandhi & Ness, 2019

But beware working with Actions

not invariant quantities over time due to break down of assumptions calculated under (disk is busy)

The Galactic Midplane Is Not a Plane: Implications for Dynamical Analysis with *Gaia* Data and Beyond

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Submitted to ApJ

ABSTRACT

Orbital properties of stars, computed from their six-dimensional phase space measurements and an assumed Galactic potential, are used to understand the structure and evolution of the Galaxy. Stellar actions, computed from orbits, have the attractive quality of being invariant under certain assumptions and are therefore used as quantitative labels of a star's orbit. We report a subtle but important systematic error that is induced in the actions as a consequence of local midplane variations expected for the Milky Way. This error is difficult to model because it is non-Gaussian and bimodal, with neither mode peaking on the null value. An offset in the vertical position of the Galactic midplane of $\sim 15\,\mathrm{pc}$ for a thin disk-like orbit or $\sim 120\,\mathrm{pc}$ for a thick disk-like orbit induces a 25% systematic error in the vertical action J_z. In FIRE simulations of Milky Way-mass galaxies, these variations are on the order of $\sim 100\,\mathrm{pc}$ at the solar circle. From observations of the mean vertical velocity variation of ~ 5–$10\,\mathrm{km\,s^{-1}}$ with radius, we estimate that the Milky Way midplane variations are ~ 60–$170\,\mathrm{pc}$, consistent with three-dimensional dust maps. Action calculations and orbit integrations, which assume the global and local midplanes are identical, are likely to include this induced error, depending on the volume considered. Variation in the local standard of rest or distance to the Galactic center causes similar issues. The variation of the midplane must be taken into account when performing dynamical analysis across the large regions of the disk accessible to *Gaia* and future missions.

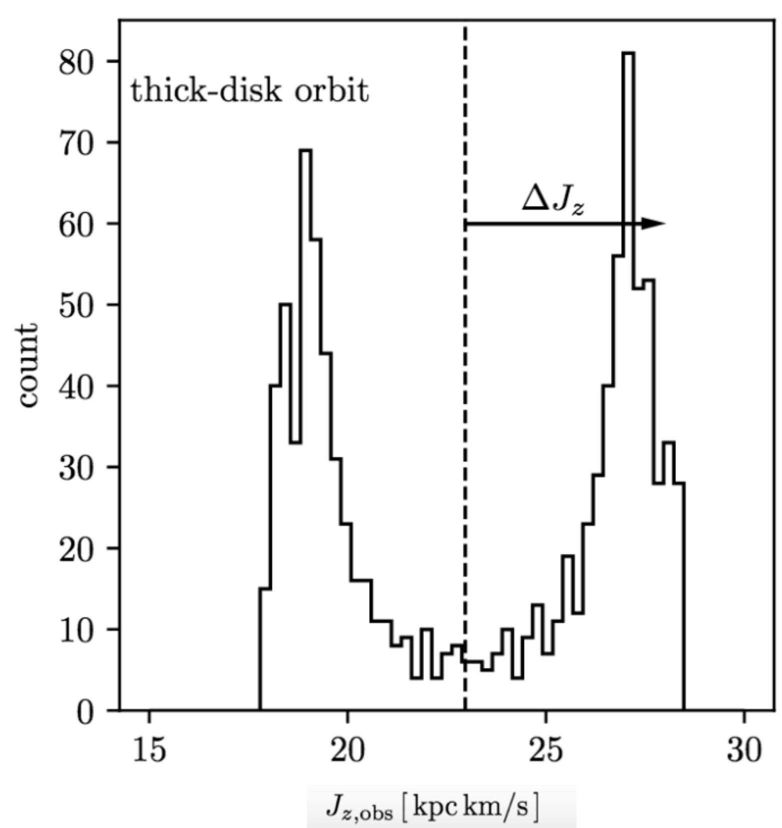
Keywords: Milky Way disk – Milky Way dynamics – Milky Way evolution – Galaxy structure – Orbits – Stellar dynamics

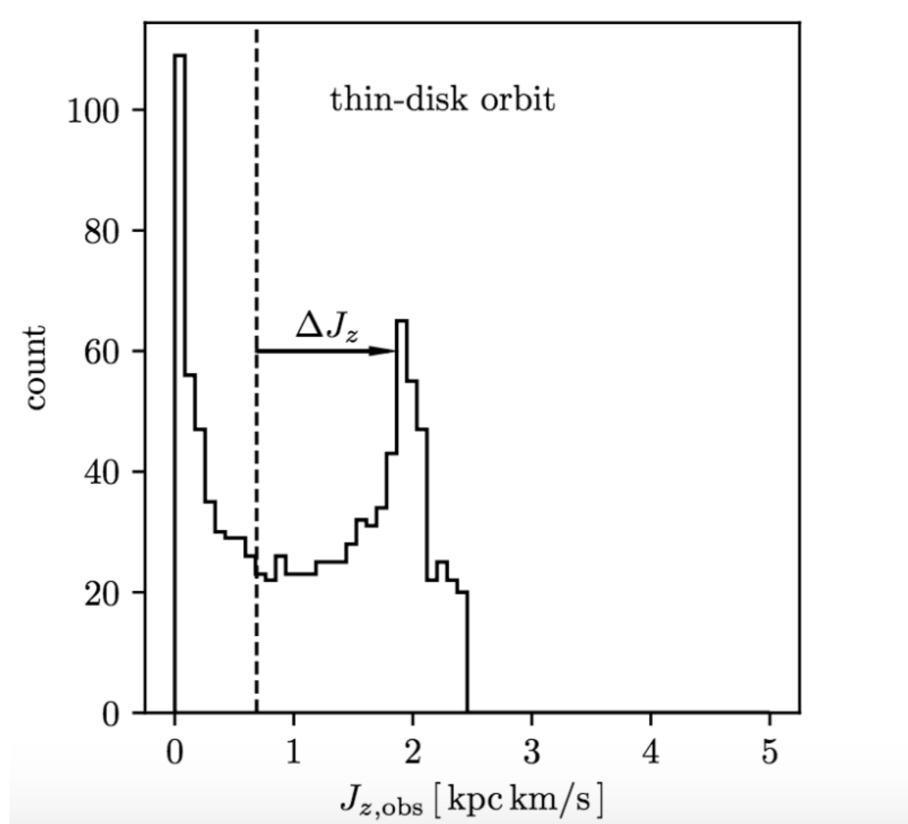
Beane et al., 2019

Induced error is not Gaussian

not invariant quantities over time due to break down of assumptions calculated under (disk is busy)

name	initial position	initial velocity	J_R	J_ϕ	J_z	$z_{\max}$	A_R
	kpc	km/s	$\mathrm{kpc\,km\,s^{-1}}$	$\mathrm{kpc\,km\,s^{-1}}$	$\mathrm{kpc\,km\,s^{-1}}$	kpc	kpc
thin-disk	$(8, 0, 0)$	$(0, -190, 10)$	40.3	-1520	0.69	0.12	1.29
thick-disk	$(8, 0, 0)$	$(0, -190, 50)$	32.5	-1520	23.0	0.85	1.19
halo	$(8, 0, 0)$	$(0, -190, 190)$	32.8	-1520	529.1	6.16	2.34

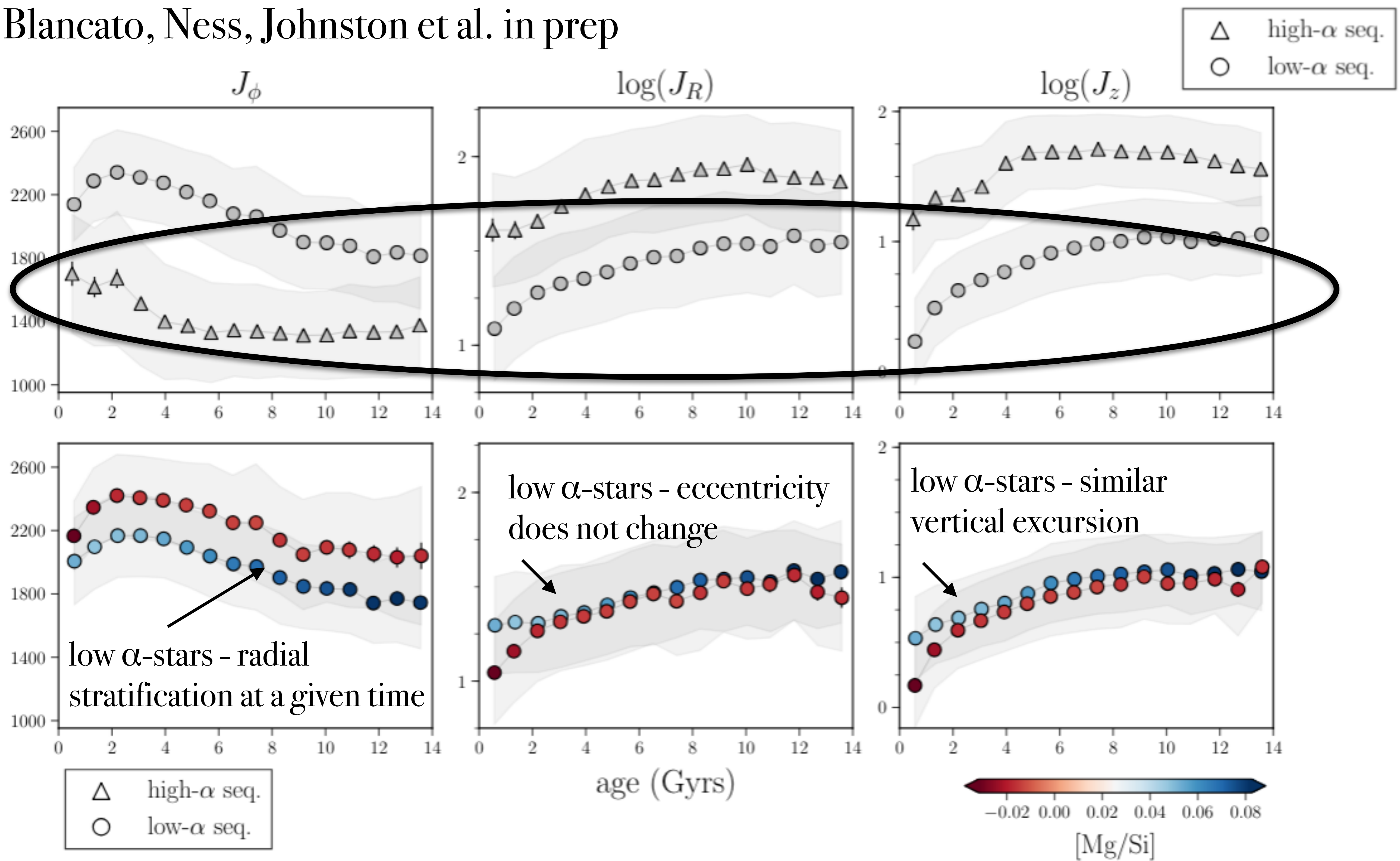




ane et al., 2019

At a given age, disk radially stratified in [Mg/Fe]

Blancato, Ness, Johnston et al. in prep



So far

- The Milky Way disk has a bimodality in [α/Fe] v. [Fe/H]

- Star's membership in the high- or low-α sequence indicates its dynamical properties at a given time

- A higher level of granularity of information is encoded within the alpha-element ratios - isolate chemical enrichment events

- See that at a given time, for the low-alpha sequence, the star forming gas was radially stratified

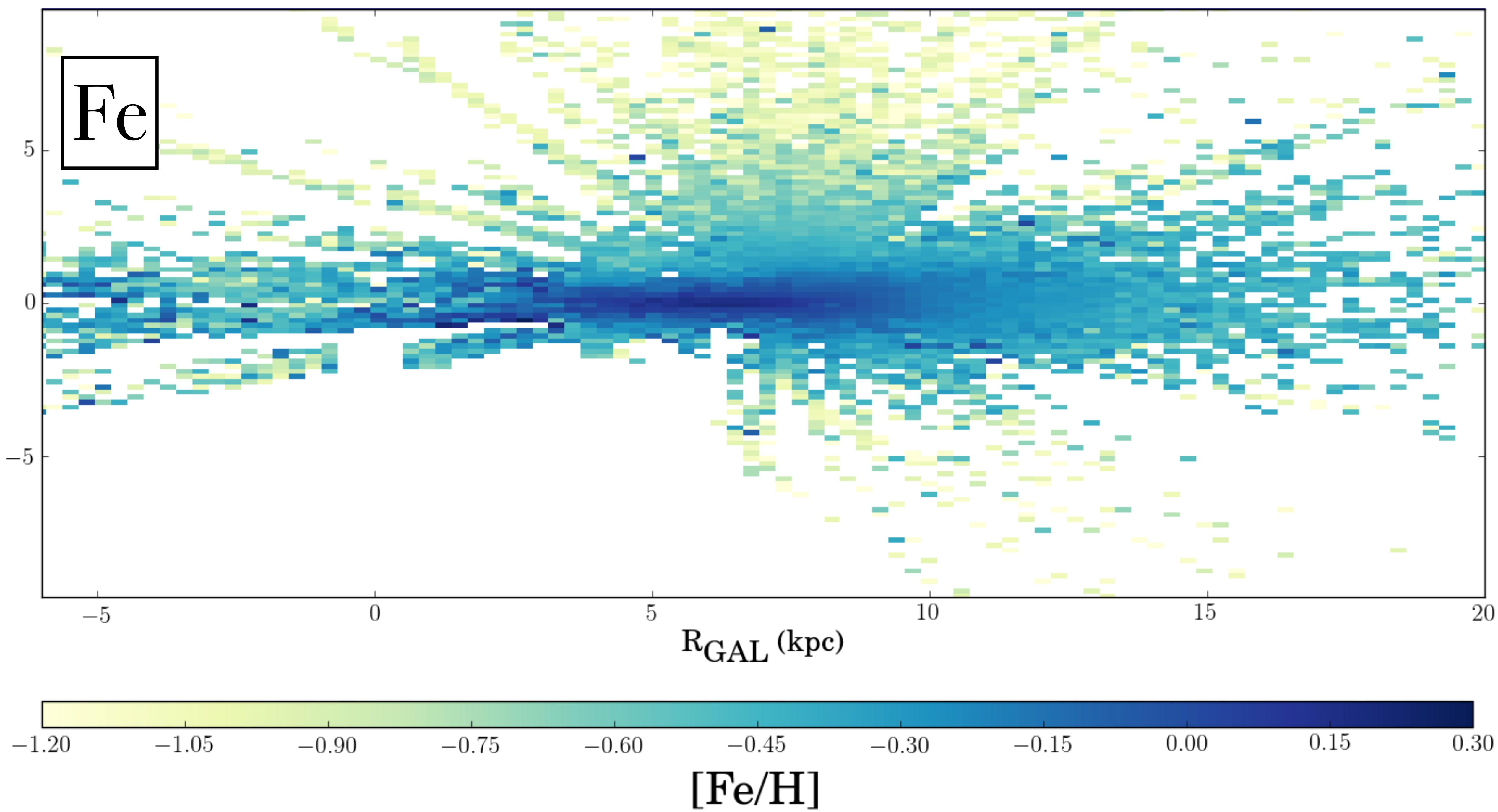
  - Beyond the α-elements

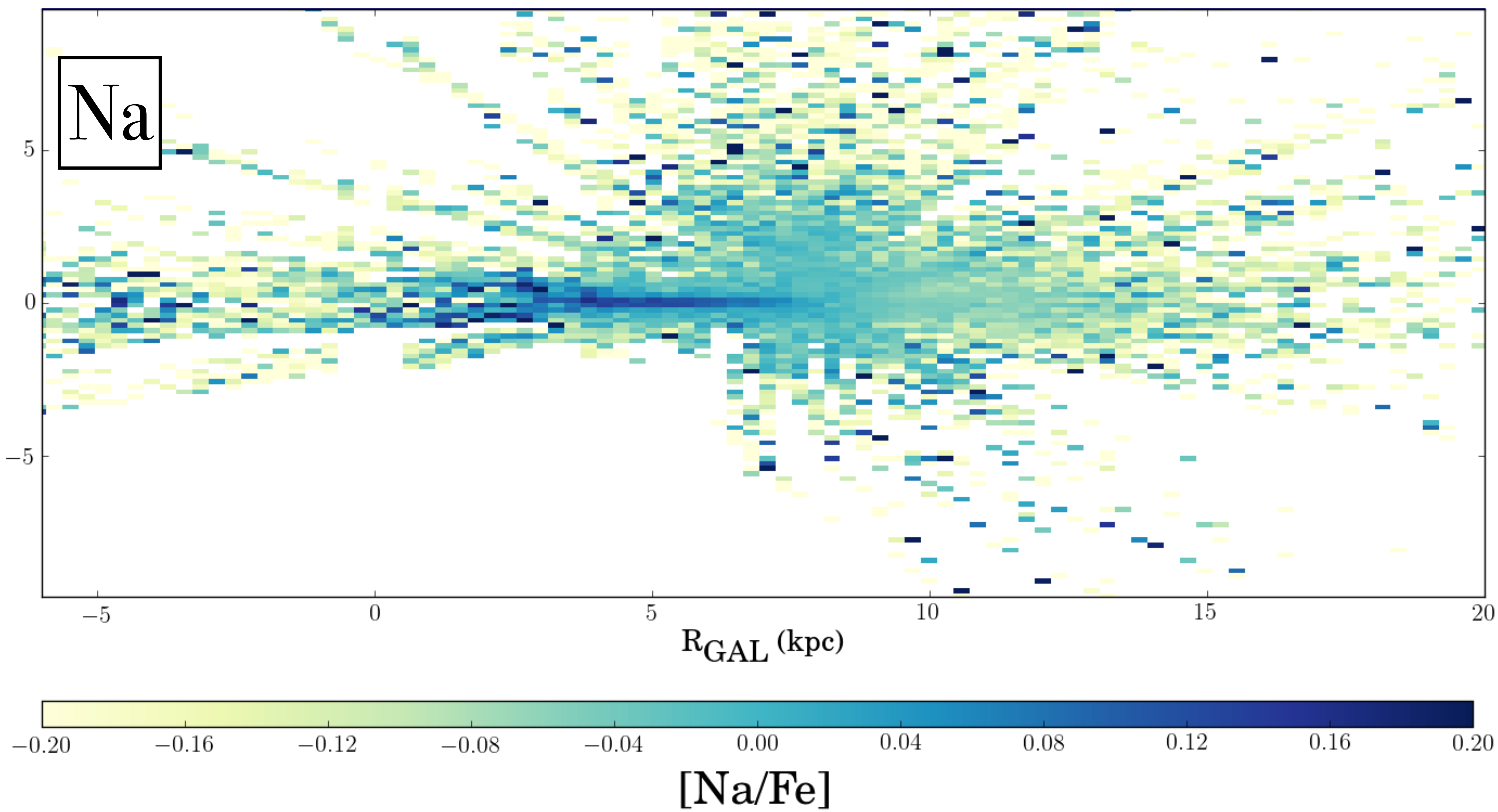
What do we learn from all of the individual abundances?

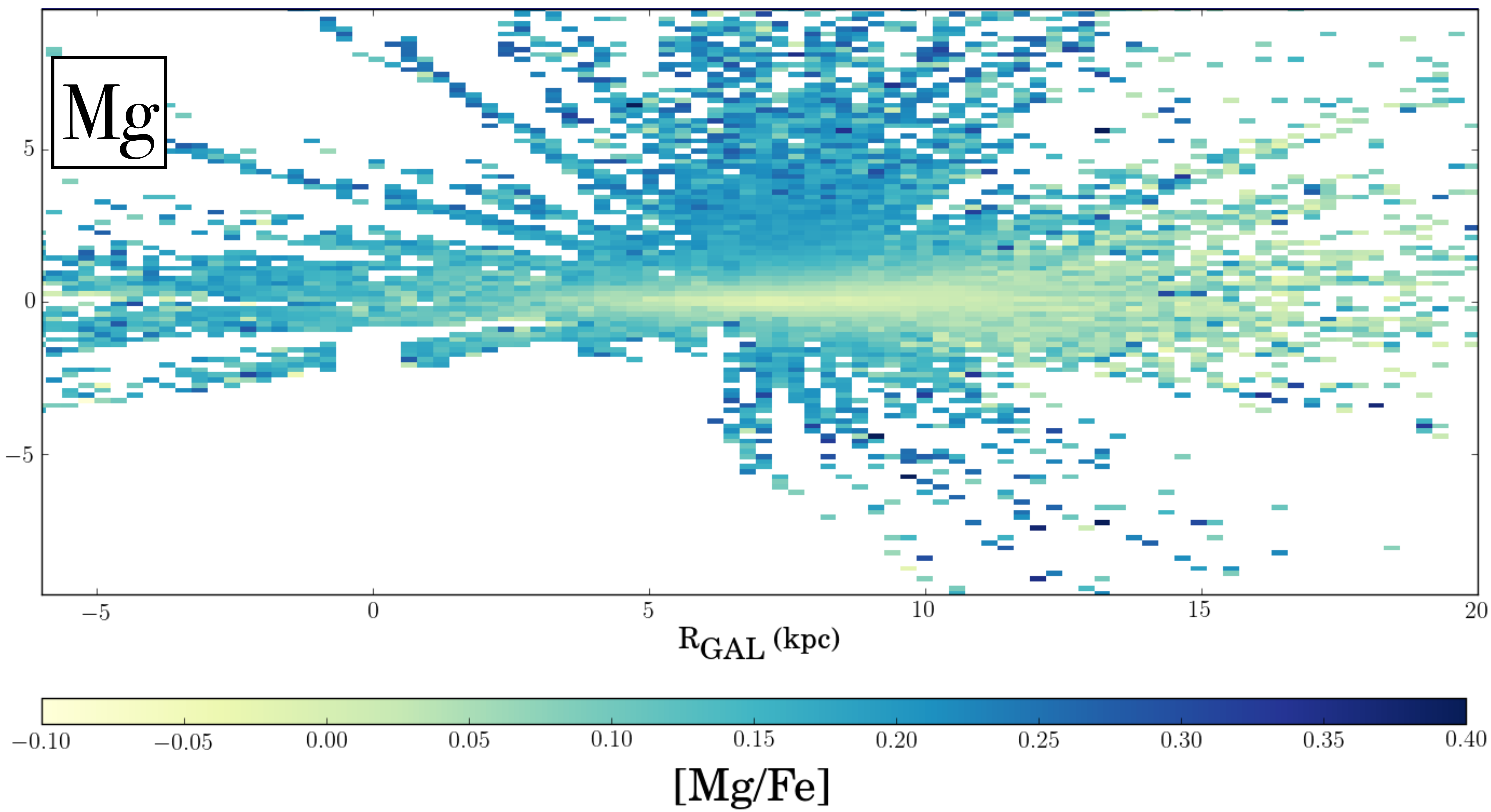
(age, [Fe/H], [X/Fe])

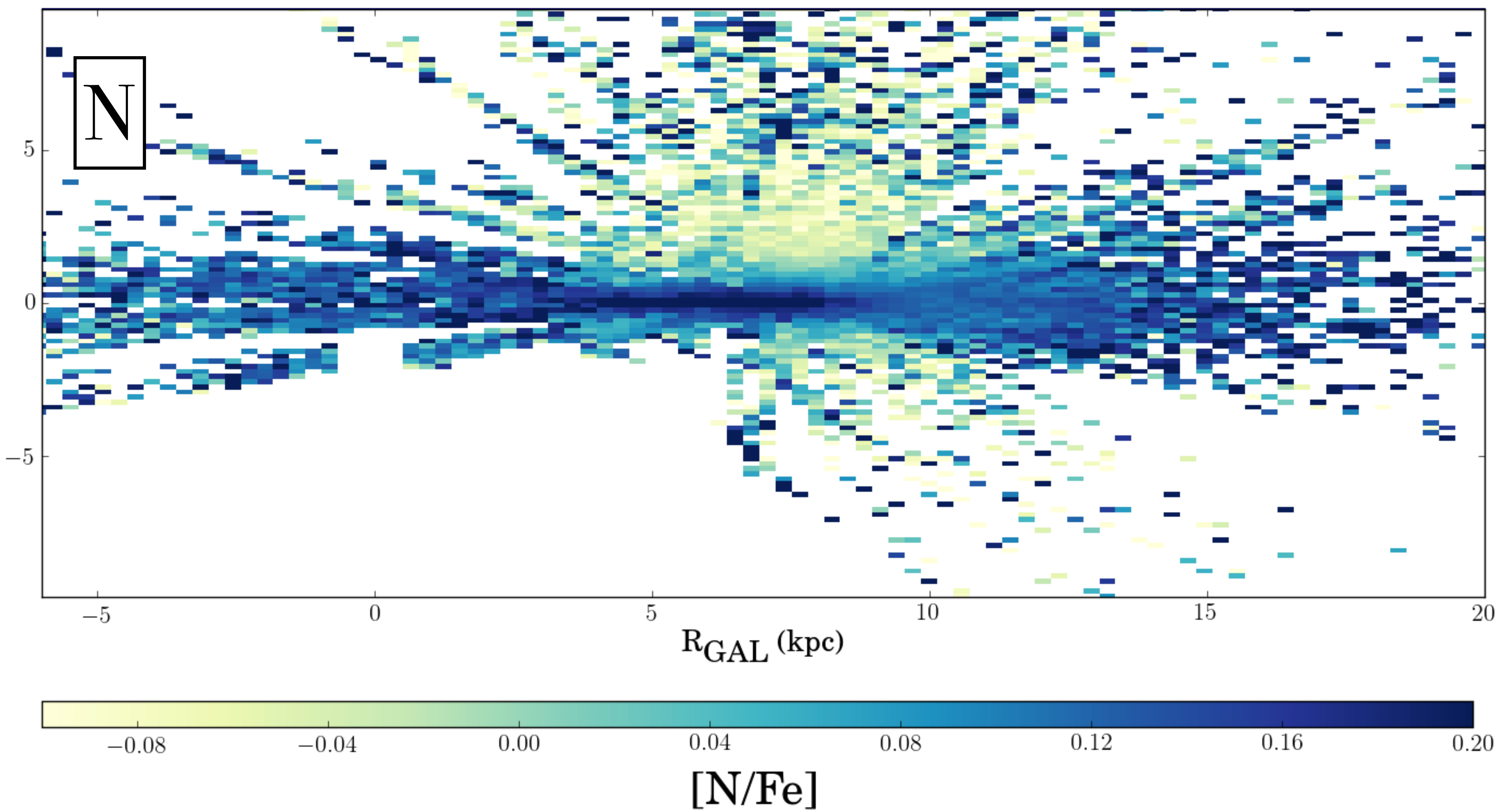
what does the [X/Fe] tell us?

This is what APOGEE looks like




Na
5
0
−5
−5
0
5
10
15
20
R_GAL (kpc)
−0.20
−0.16
−0.12
−0.08
−0.04
0.00
0.04
0.08
0.12
0.16
0.20
[Na/Fe]


Mg
5
0
−5
−5
0
5
10
15
20
R_GAL (kpc)
−0.10
−0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
[Mg/Fe]


N
5
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−5
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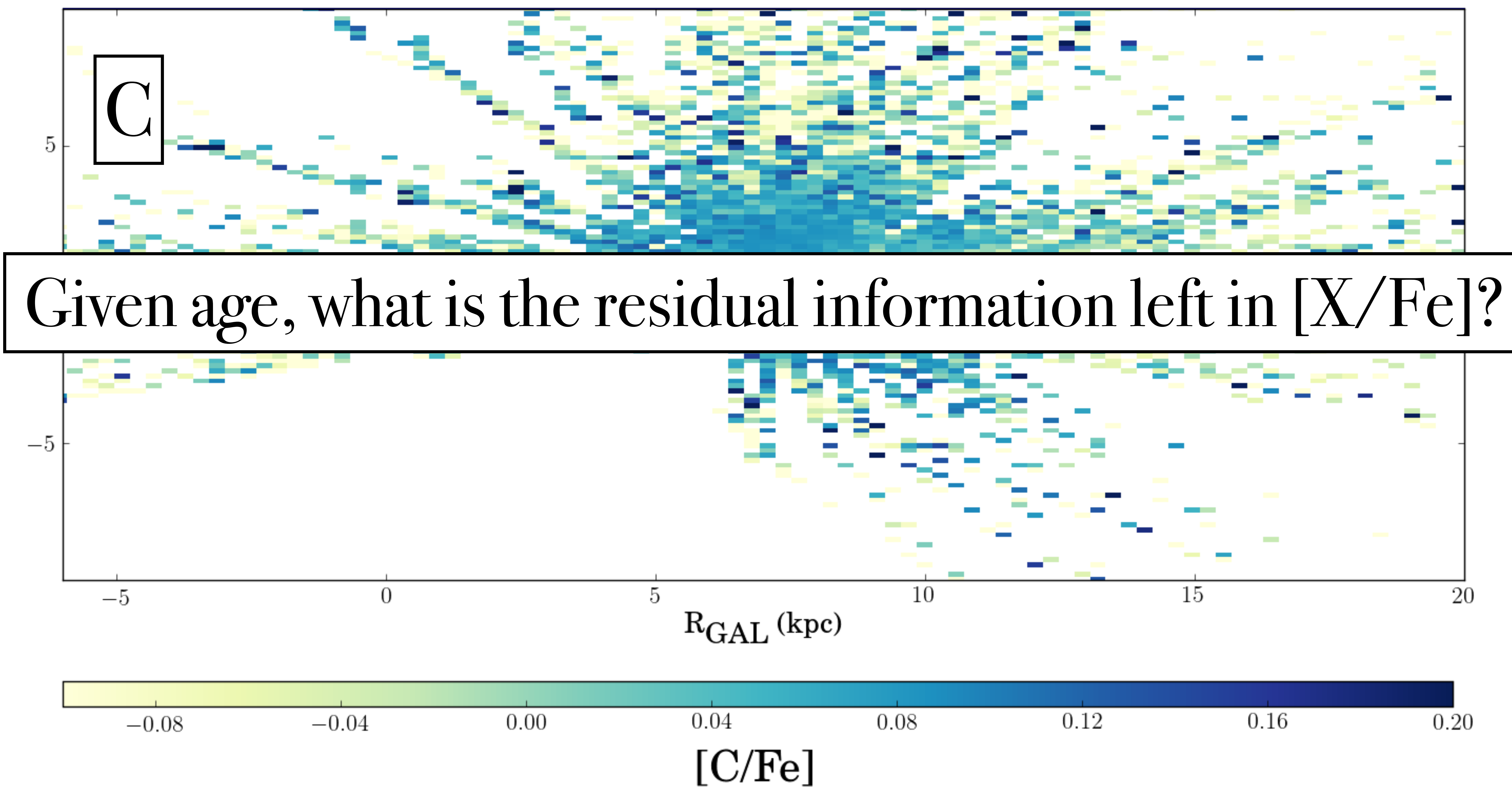
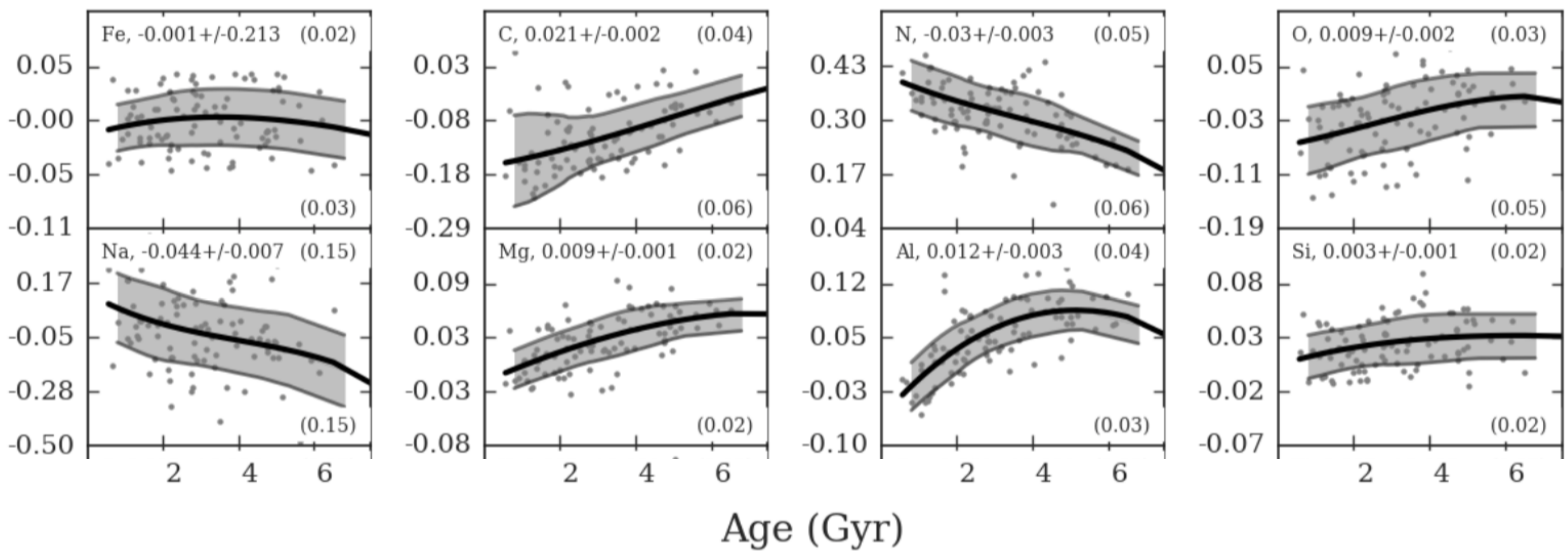
5
10
15
20
RGAL (kpc)
−0.08
−0.04
0.00
0.04
0.08
0.12
0.16
0.20
[N/Fe]


C
Given age, what is the residual information left in [X/Fe]?
5
−5
−5
0
5
10
15
20
RGAL (kpc)
−0.08
−0.04
0.00
0.04
0.08
0.12
0.16
0.20
[C/Fe]

The abundance-age relations in the disk

- age-abundance relations for 8 of 18 elements measured in APOGEE



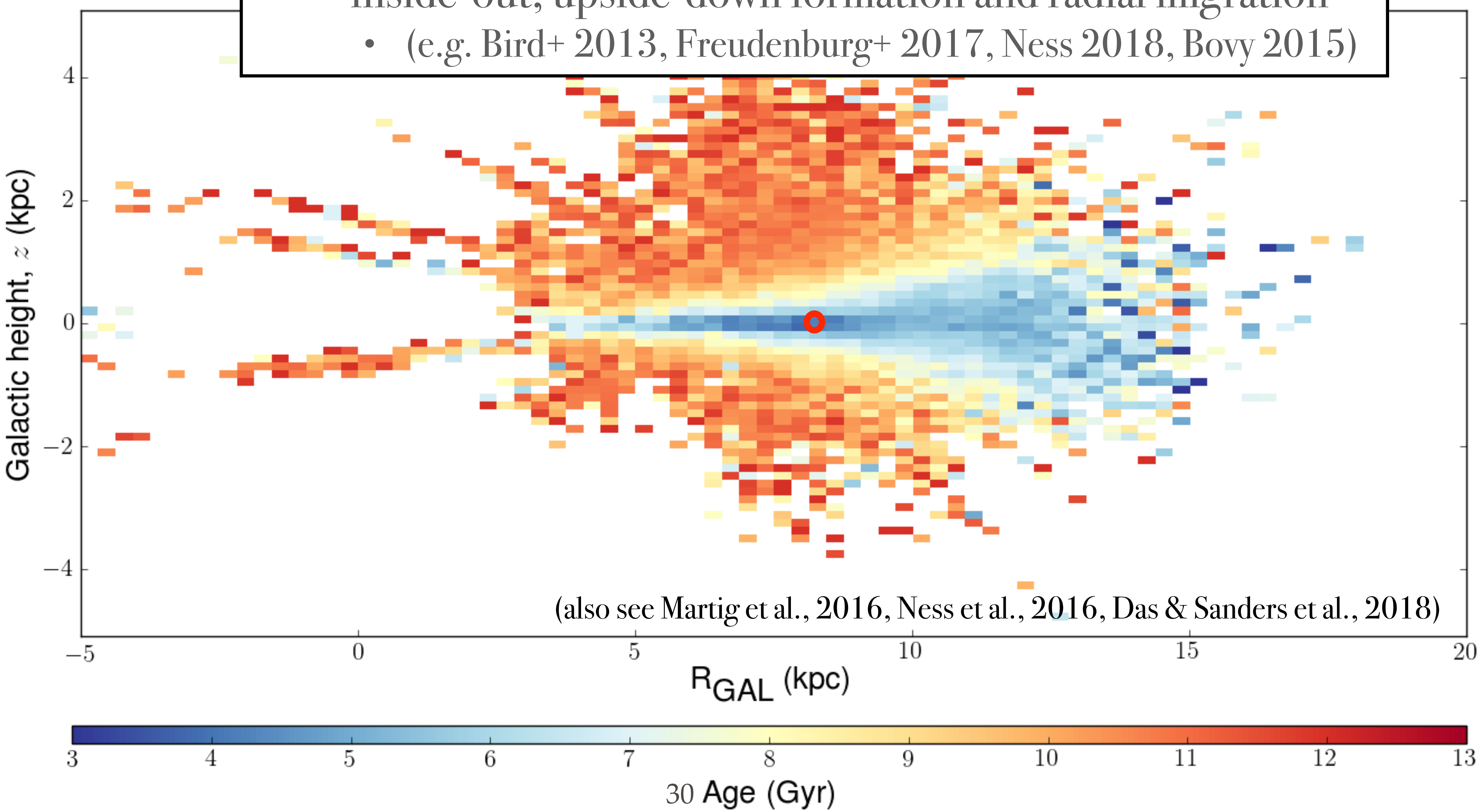
- for 1000 red clump giants with [Fe/H] = 0 with ages from asteroseismology (low-α disk)

Ness in prep 2019

Ages: inside out formation and flaring of the disk

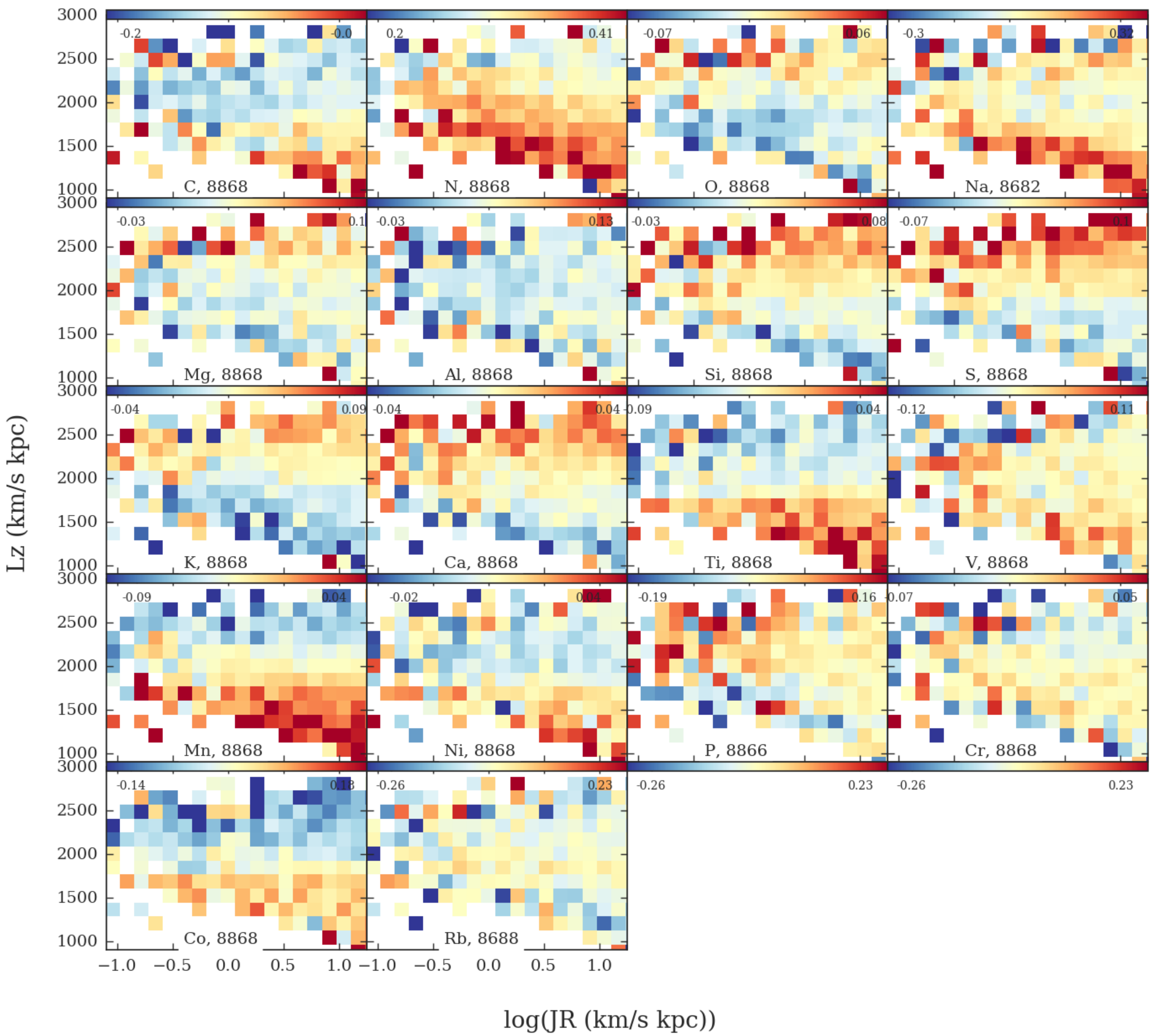
- inside-out, upside-down formation and radial migration
  - (e.g. Bird+ 2013, Freudenburg+ 2017, Ness 2018, Bovy 2015)

R14



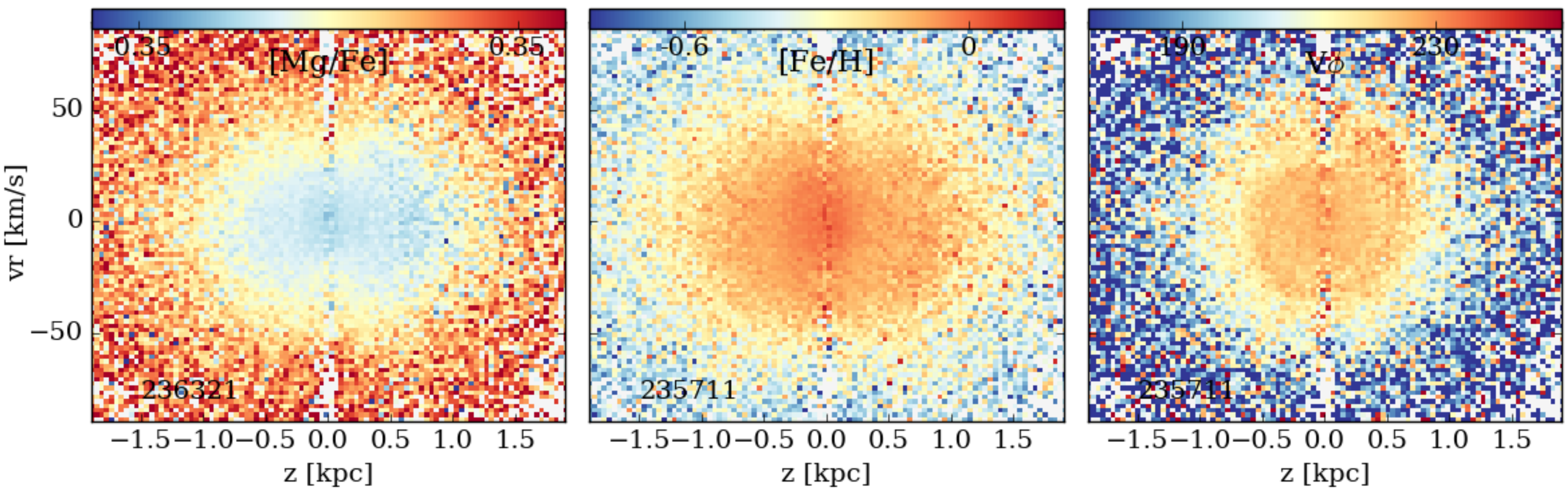
(also see Martig et al., 2016, Ness et al., 2016, Das & Sanders et al., 2018)

There are abundance-dynamics correlations



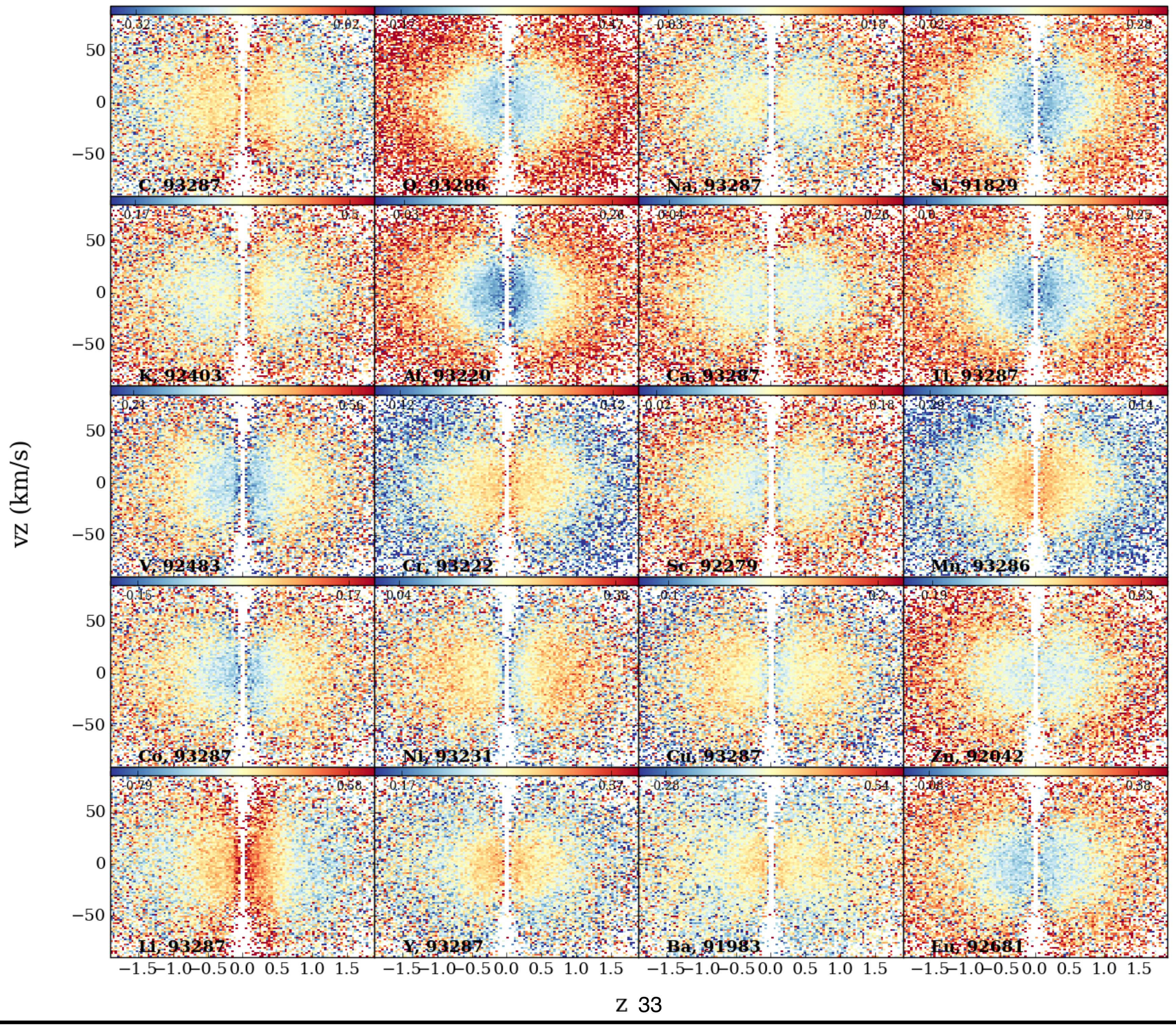
There are abundance-dynamics correlations

[Mg/Fe] [Fe/H] v_ϕ



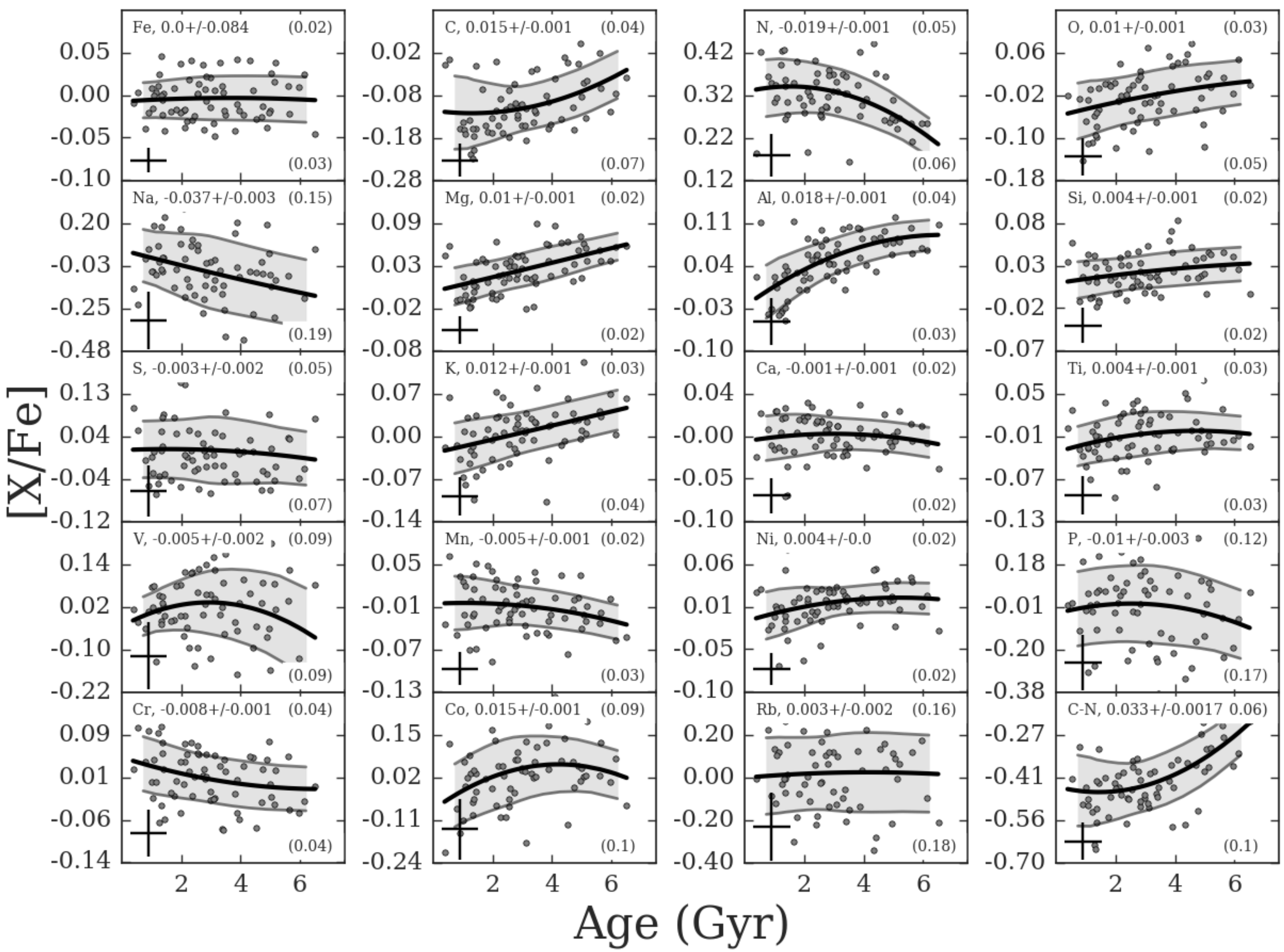
see Antoja 2018 - the spiral

There are abundance-dynamics correlations



Why is there structure everywhere?
Is there some fundamental variable
linking everything?

Yes, age



Open questions

(Q1) This is for the low-α sequence (at left). What does this look like for the high-α sequence?

(Q2) how does the ratio of inter-family elements beyond alpha e.g. Cr/Co vary across the disk? What does this tell us about the disk evolution>

Resources: APOKASC & APOKASC & GAIA

1) **APOKASC** – stars observed by both APOGEE & Kepler
http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=J/ApJS/239/32

2) APOGEE DR14 https://www.sdss.org/dr14/irspec/spectro_data/

3) Gaia - Gaia archive

- Can cross-match to get APOGEE+Gaia and then APOGEE+Gaia+APOKASC

Chemical compositions

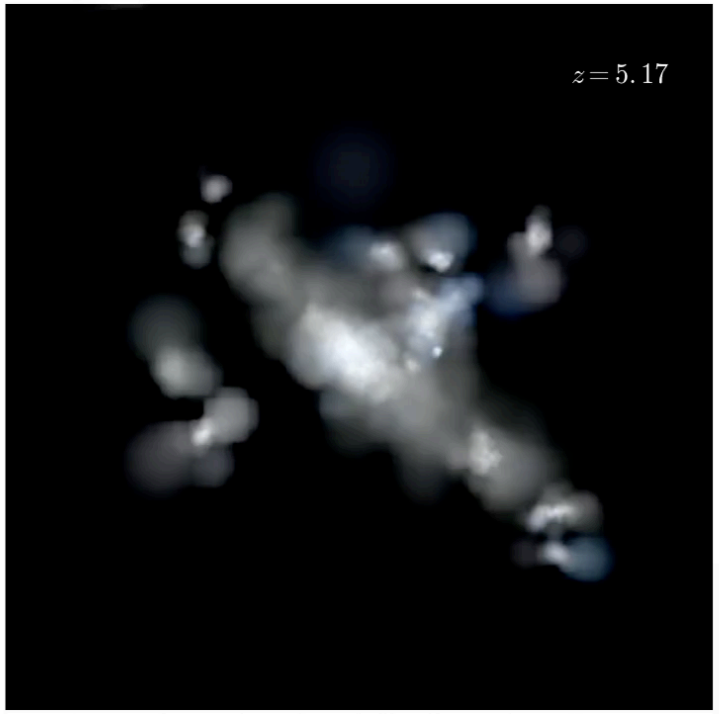
Reconstruct the enrichment history of the disk

hundreds of thousands of stars with high precision [X/Fe] measurements

Chemical compositions to reconstruct enrichment history

Early turbulent formation ⟶ settles into Galactic disk (75% of stellar mass)

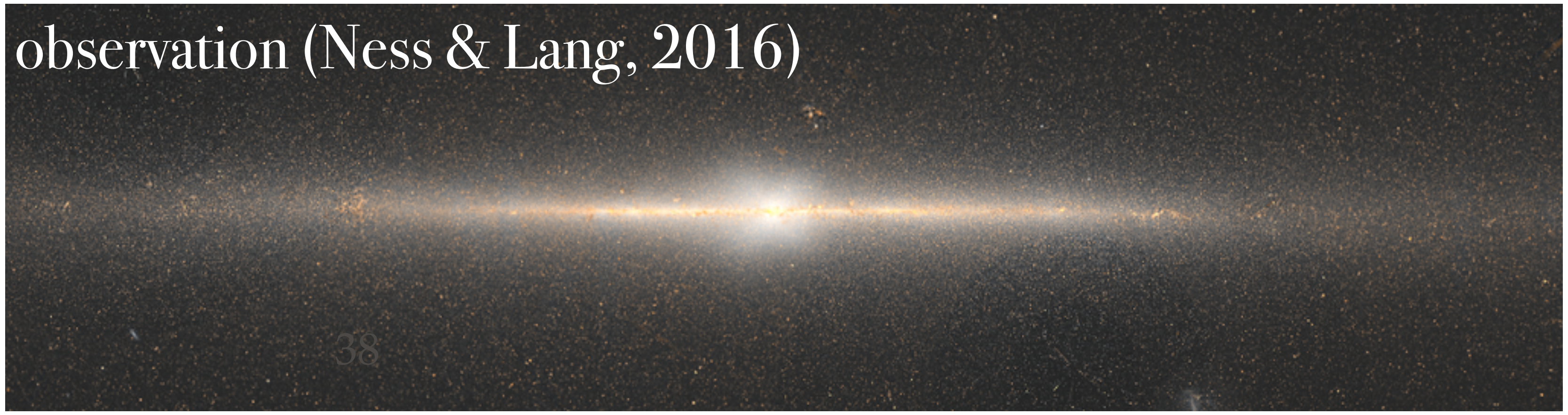
Animation by T. Buck (MPIA, NYUAD) based on NIHAO simulations



Animation by T. Buck (MPIA, NYUAD) based on NIHAO simulations

Buck et al., 2018

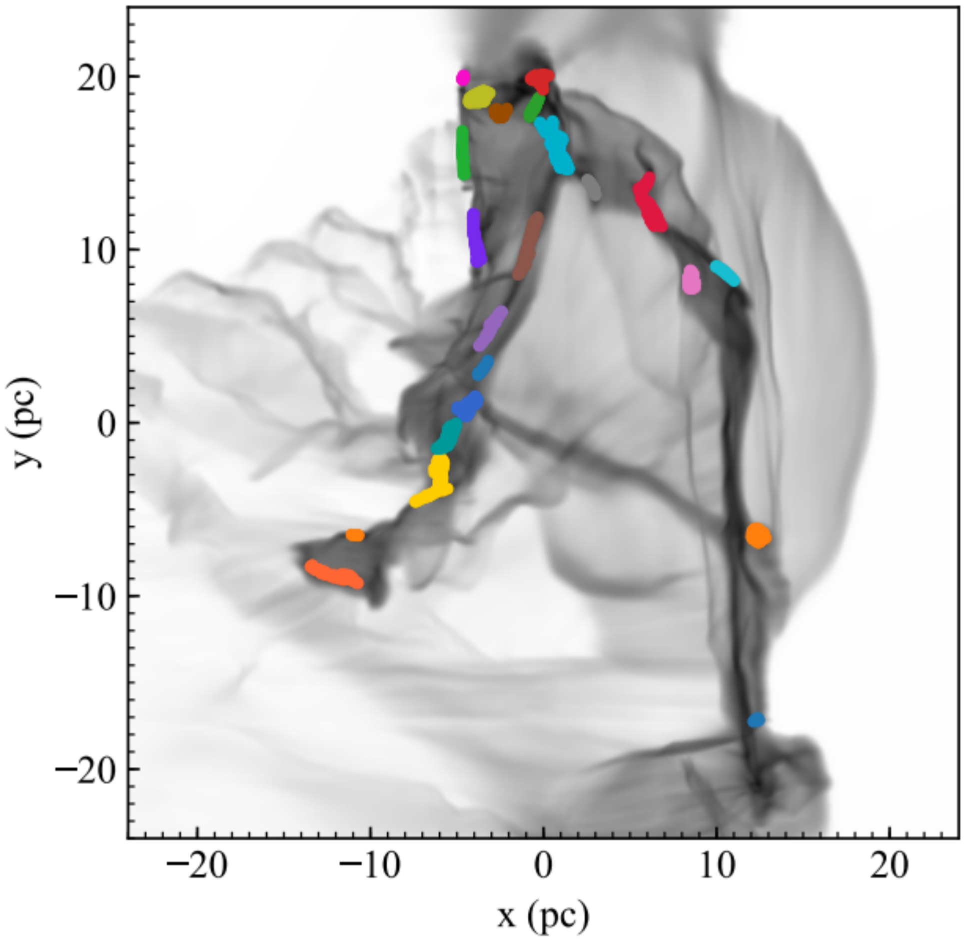
positions and dynamics change, chemical compositions birth properties



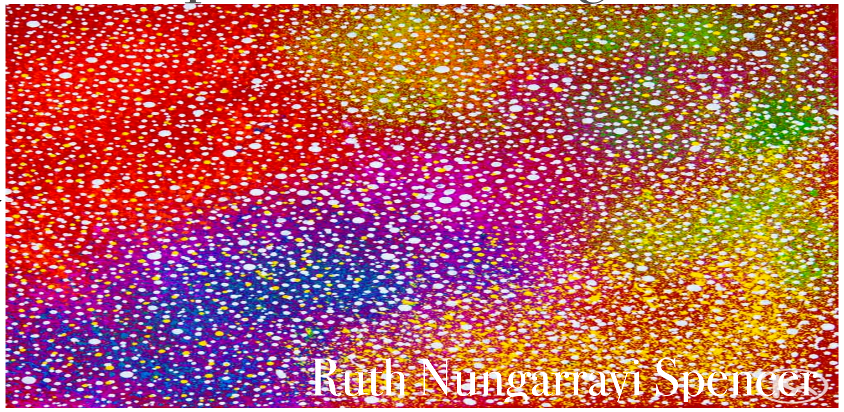
Where are stars born?

- Stars form in clusters, with presumably identical abundances

Armillotta et al., 2018



these disperse in forming the disk



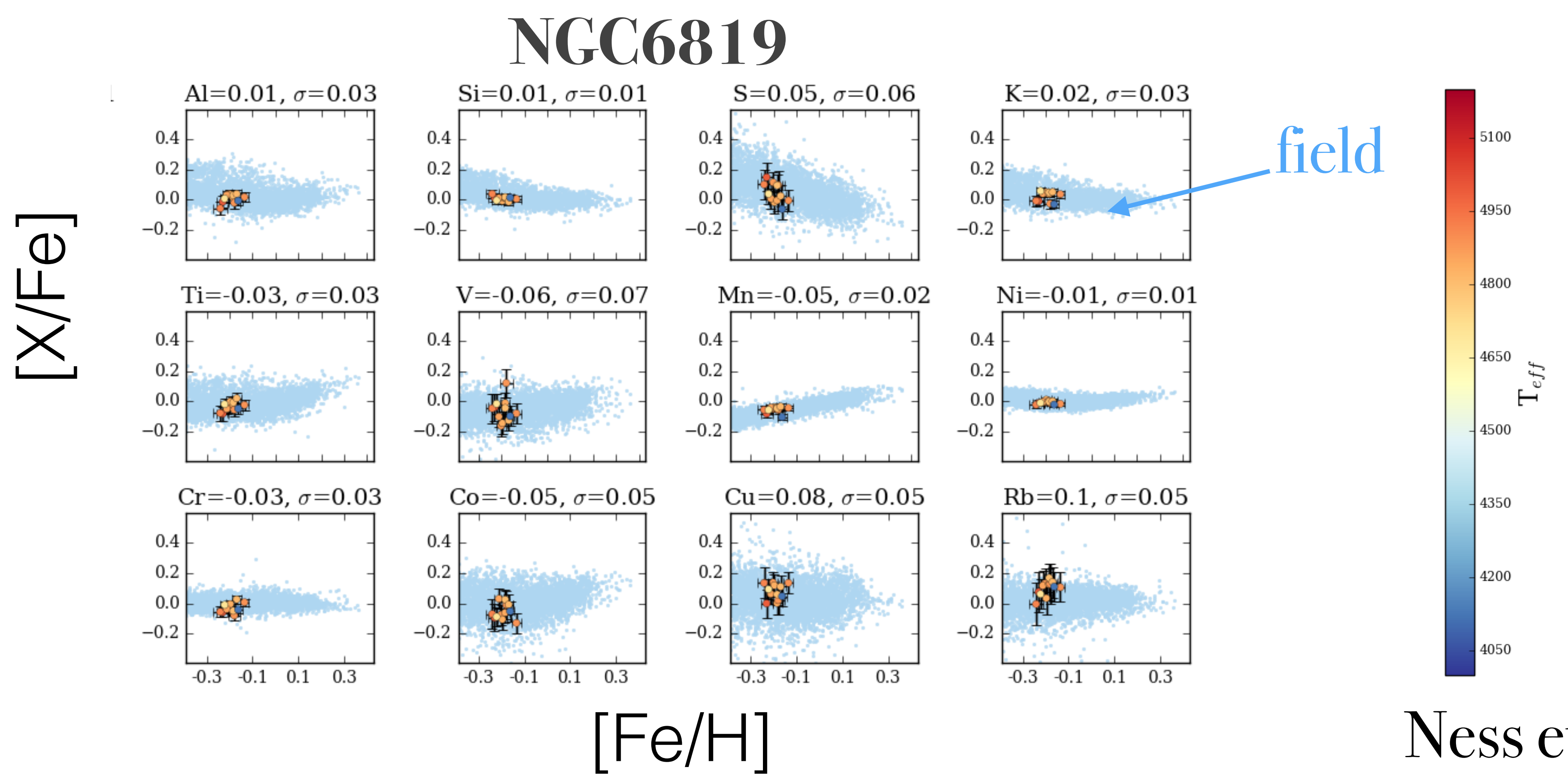
- one prospect to trace back disk assembly – identify individual stars across the disk from the same birth sites using large vector of chemical abundances – **chemical tagging** (Bland-Hawthorn & Freeman 2010)

how similar in chemical abundances do we expect a random pair of stars to be, compared to stars formed together in a cluster?

Can chemical tagging work?

Step 1) Examine groups of stars known to be born together with the same chemical compositions

APOGEE targeted known **open clusters**: set the expectation for how similar stars of a common birth site are expected to be (used 100 stars in 7 clusters)

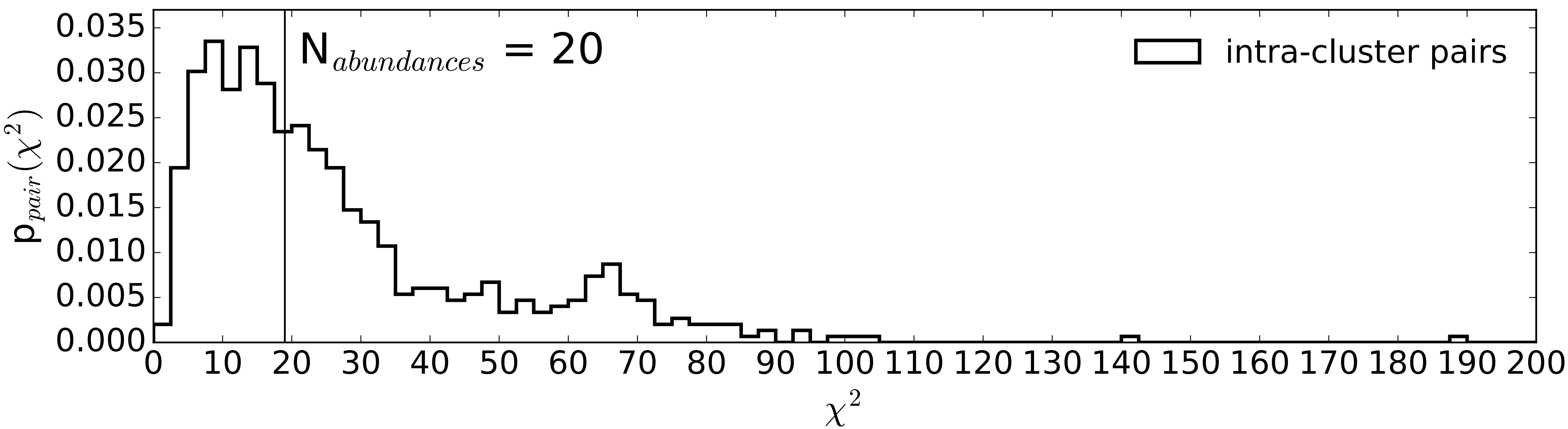


Ness et al., 2018

Abundance similarity of birth siblings

$$\chi^2_{nn'} = \sum_{i=1}^{I} \frac{[x_{ni} - x_{n'i}]^2}{\sigma^2_{ni} + \sigma^2_{n'i}}.$$

where the indices n and n' denote the two stars, i the elements, and x_{ni} the measurements with uncertainty σ_{ni}.

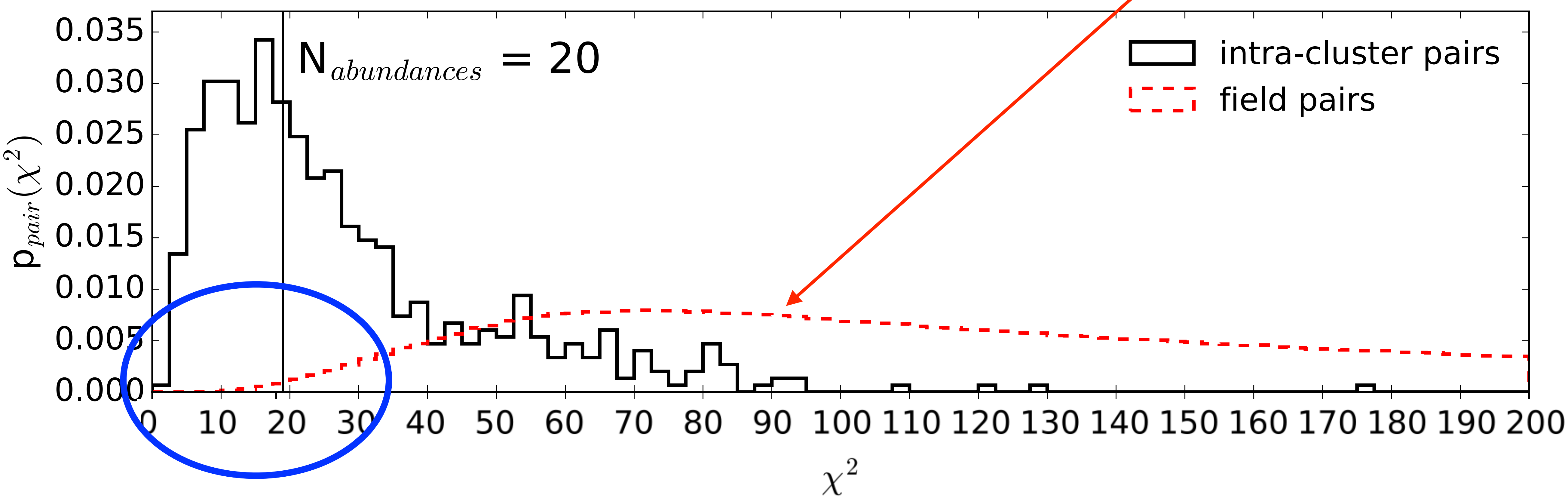


Most stars within a cluster have abundances in *most* elements that are indistinguishable from those of the other members, as expected for stellar birth siblings.

Ness et al., 2018

Abundance similarity of random field pairs

An analogous analysis among pairs of 2000 field stars (red):



highly significant abundance differences for the vast majority of field pairs

APOGEE -based abundance measurements have high discriminating power

* * * Pairs of field stars whose abundances are indistinguishable (even at 0.03 dex precision exist) and are not very rare* *

Ness et al., 2018

20 January 2017

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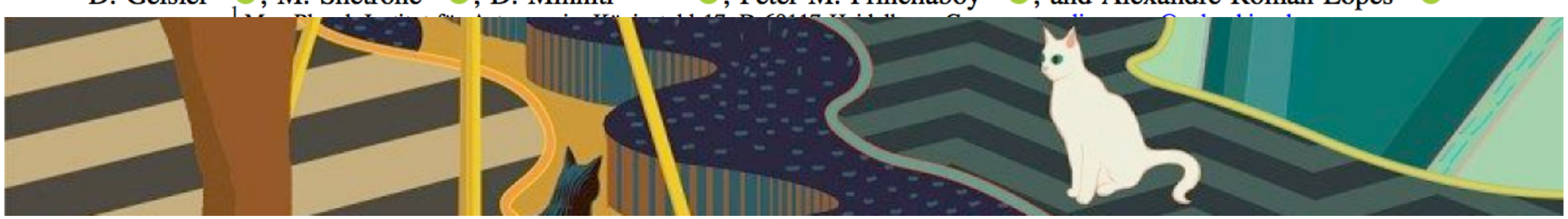
How far away is your doppelgänger?

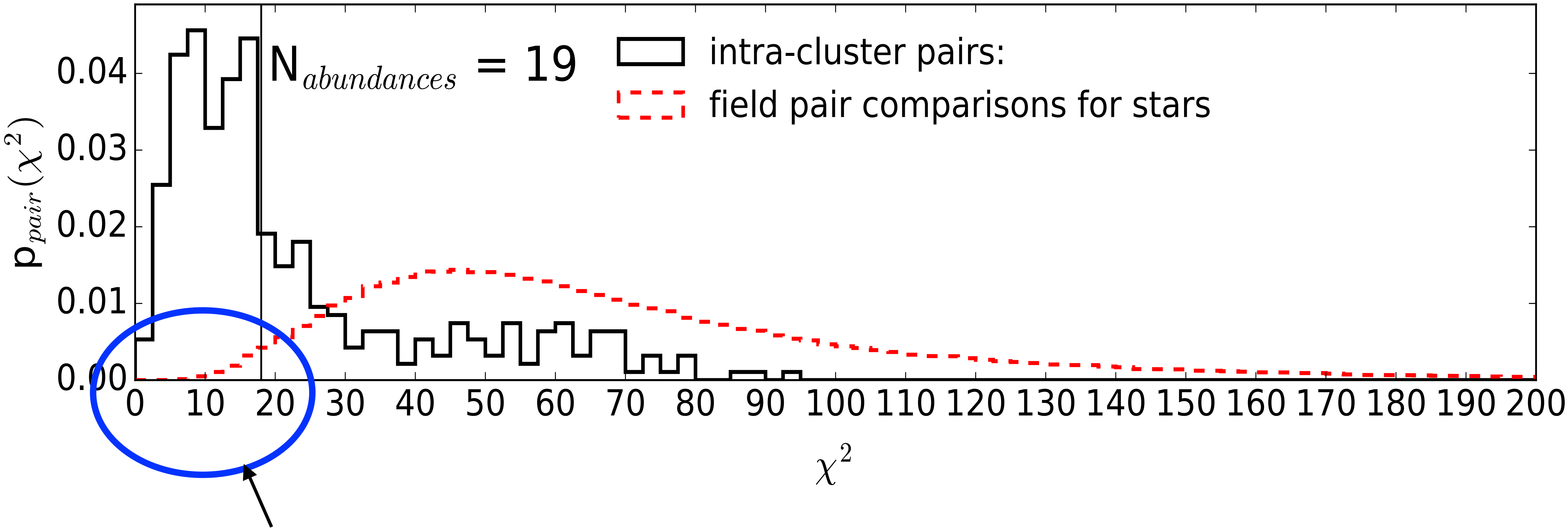
THE ASTROPHYSICAL JOURNAL, 853:198 (22pp), 2018 February 1
https://doi.org/10.3847/1538-4357/aa9d8e

Galactic Doppelgängers: The Chemical Similarity Among Field Stars and Among Stars with a Common Birth Origin

M. Ness[1,2,3], H-W. Rix[1], David W. Hogg[1,3,4,5], A. R. Casey[6], J. Holtzman[7], M. Fouesneau[1], G. Zasowski[8,9], D. Geisler[10], M. Shetrone[11], D. Minniti[12,13,14], Peter M. Frinchaboy[15], and Alexandre Roman-Lopes[16]



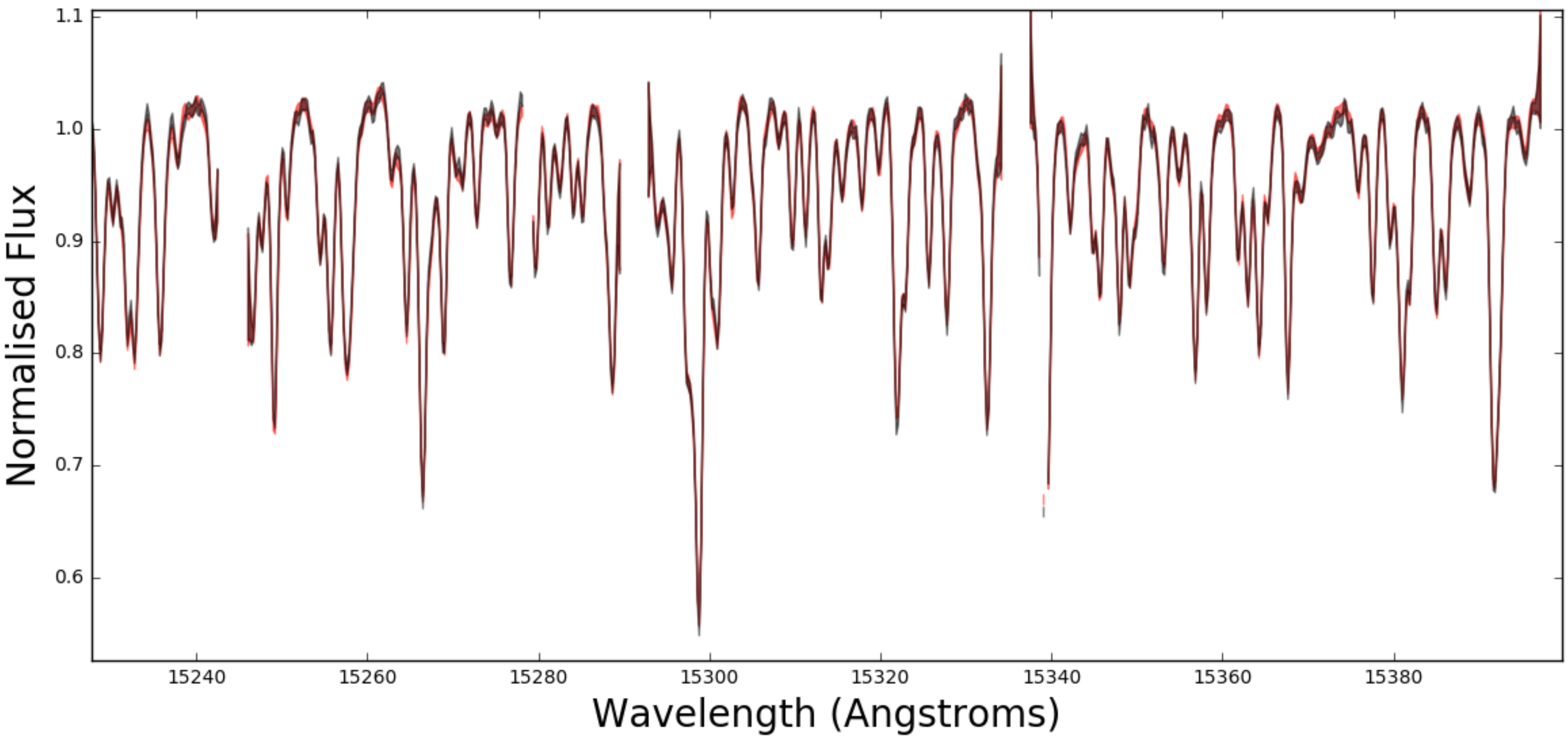
Abundance similarity of random field pairs



1.0% of field pairs at solar metallicity have χ^2 differences as small as the median χ^2 among intra-cluster pairs: these stars are doppelgänger

How similar are stars to one another?

– in APOGEE, 1 in 100 stars are chemically identical (20 elements) –



Galactic Doppelgängers: implications

Optimistically, cluster mass at most = 1×10^6 M_{sun} and disk mass = 1×10^{10} M_{sun}

- Then, expect 1 in 10,000 random pairs to be true birth siblings (1×10^{-4})

- We find 1 in 100 field pairs are as similar as birth siblings– *doppelgänger* (1×10^{-2})

Not much point in trying to reconstruct individual formation sites from [X/Fe]

- Have to make sense of the overall distribution of **p(orbit, [X/Fe], ages, R_{GAL})**

- relevant to this aim: large numbers & complete spatial coverage & statistical analyses

[X/Fe] & orbits together..Galactic archeology

Stars that Move Together Were Born Together, Kamdar et al., 2019
https://ui.adsabs.harvard.edu/abs/2019arXiv190402159K/abstract

co-natal stars should be present throughout the Galaxy, and their demographics can shed light on the clustered nature of star formation and the dynamical state of the disk

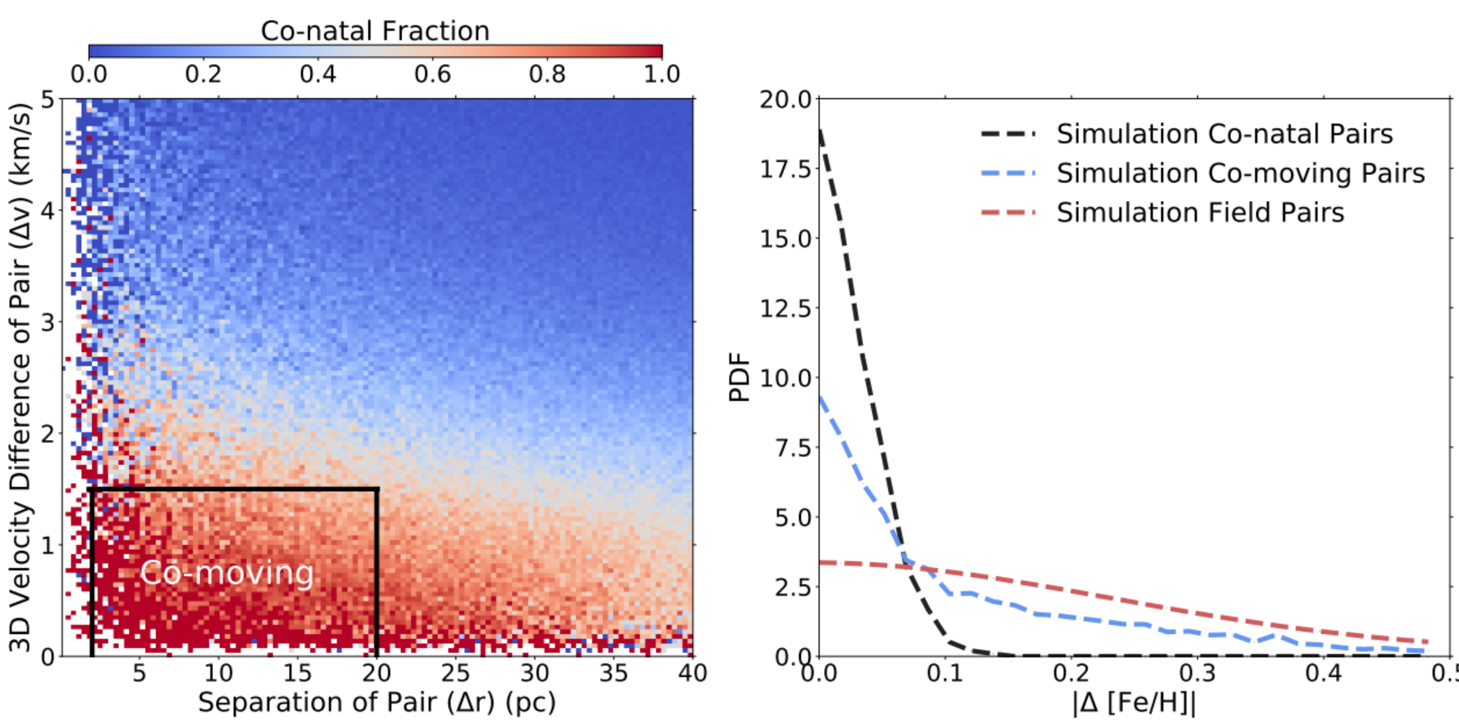


Figure 2. Left Panel: Co-natal fraction of pairs as a function of separation (Δr) and 3D velocity difference (Δv). Pairs with $2 < \Delta r < 20$ pc and $\Delta v < 1.5$ km s^{-1} have a notably high co-natal fraction – the selection box is used to define "co-moving" pairs. Right Panel: Expected difference in metallicites of stars in a pair. The blue line shows the metallicity difference distribution for all co-moving pairs, while the red line shows the metallicity difference distribution for random field pairs in the solar neighborhood sample. The black line shows the metallicity difference for the subset of co-moving pairs that are also co-natal. The simulation adopts $\sigma_{[Fe/H]} = 0.03$ dex.

statistical analyses and comparison to analytic model or simulation

[X/Fe] & orbits together..stars & their families

Kronos and Krios: Evidence for Accretion of a Massive, Rocky Planetary System in a Comoving Pair of Solar-type Stars, Oh et al., 2018
https://ui.adsabs.harvard.edu/abs/2018ApJ...854..138O/abstract

Significant difference in the chemical abundances of a comoving pair of bright solar-type stars

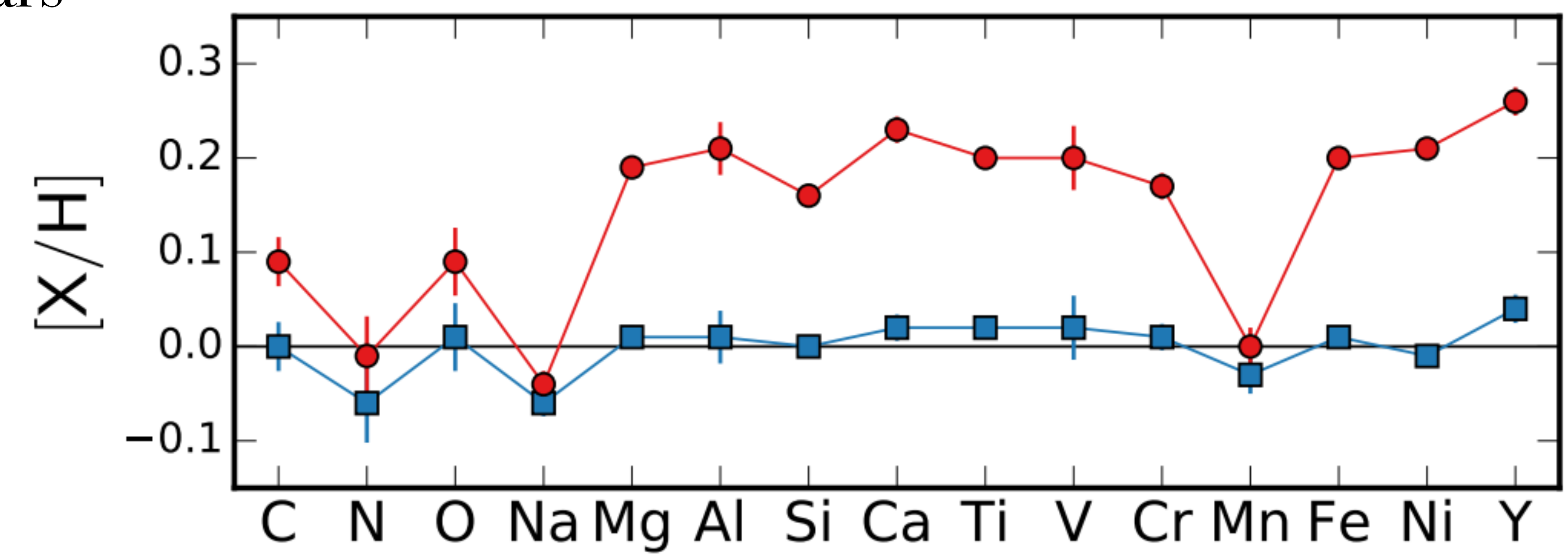


Figure 2. Abundances of the comoving pair, Krios (blue) and Kronos (red). Lines are drawn for each star only to guide the eye. Kronos is enhanced in Fe by ≈ 0.2 dex relative to Krios along with Mg, Al, Si, Ca, Ti, V, Cr, Ni, Y yet not in C, N, O, Na, and Mn.

Discussion & Blackboard work

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